Bachelor thesis on:

Performance of farm trees in farming systems in Mubende district, Uganda

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Abstract

The research of this thesis will focus on the performance of farm forestry trees in Mubende district, Uganda. In order to this, the research will help to fill the existing knowledge gap on the performance of farm forestry trees of east Africa specially Uganda. The conducted tree species are *Markhamia lutea, Ficus natalensis, Mangifera indica, Artocarpus heterophyllus, Anitaris toxicaria, Persea americana, Albizia coriaria* and *Spathodea campanulata.* The selection of the trees was mainly driven through the availability of age information. The trees were measured in height, age, DBH, length of commercial stem, diameter at specific height and visual observations e.g. occurrence and stem quality. To compare the performance of the conducted tree species a regression analysis with eight different functions was carried out for each tree species. The results are reproducible Stand-Height-Curves, height curves, DBH curves and curves for the single tree volume. The decision on the best curve was made on their biological plausibility and their statistical calculations. Additionally, the farmers of the trees were interviewed about their tree species for e.g. purposes of the tree, value of the wood and their own impressions on the growth of the tree species. The recommendation for the best applicable function is the Petterson function for the Stand-Height-Curve and the function of Richards for the height-, DBH- and single tree volume curve. Still these functions shouldn't be used without comparison to other functions, especially because the used functions were developed for tree stand conditions and not specially for agroforestry conditions were the tree growth is in general higher.

Additionally, an upscaling and prediction of the monetary tree values is made on the basis of the single tree volume curves and the interview results. The prediction of the farmers possible income through the cultivation of trees is made for *Markhamia lutea, Ficus natalensis*, *Anitaris toxicaria*
and *Albizia coriaria* and assumes that 100 trees are planted on one hectare*. Albizia coriaria* 3.630 €
achieves the highest possible extra income for the farmer followed by *Ficus natalensis with* 1.300 *€, Anitaris toxicaria with* 910€ and *Markhamia lutea* with 880 €.

This thesis gives an example on the performance and possible monetary value of tree species in Mubende district, Uganda.

Further investigation is needed to fill the knowledge gap in the performance of east African tree species and their values completely.

Keywords: performance, tree growth, utilization, Uganda, East-Africa

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Acronyms

DBH	Diameter at breast height
GPS	Global Positioning System
MAI	Mean Annual Increment
MWE	Ministry of Water and Environment
NFA	National Forest Authority
SEE	Standard error of estimates
SSE	Sum of squared error
UBOS	Uganda Bureau of Statistics
UWA	Uganda Wildlife Authority

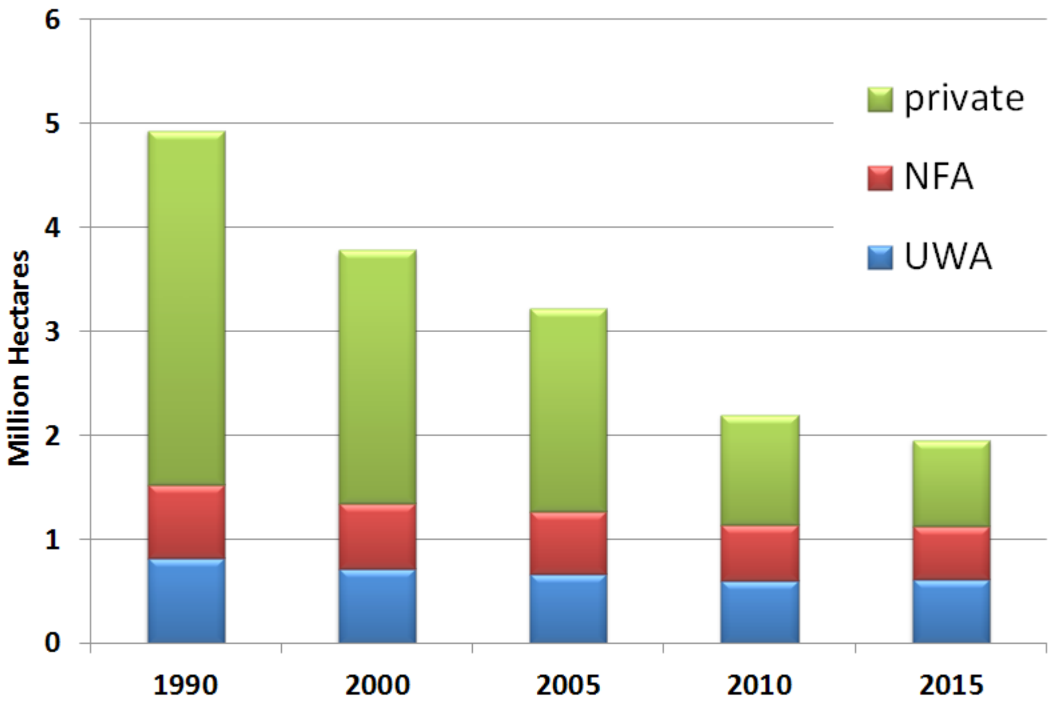
1 INTRODUCTION

1.1 Background/problem discussion

Uganda lost 46.9% (UBOS, 2017) of its forest cover during the last 20 years, which led to a forest cover of 3.8 million hectare in 2000 and a forest cover of 1.95 million hectare or 8% of the total land area in 2015 (MWE, et al., 2016). Figure 1 descripts the Forest cover of Uganda in million hectares from 19990 to 2015 in 5 years steps. The highest rate of deforestation in this time span took place in the private managed forest land which is displayed in Figure 1 in green and referred to as private. In contrast the deforestation rate of forest lands which were under control of the Uganda Wildlife Authority (UWA) in Figure 1, displayed in blue or the National Forest Authority (NFA) colored in red have a notable lower deforestation rate (MWE, et al., 2016). The main drivers for this rapid deforestation was the demand for fuel wood, the expansion of agricultural and building land and an over-harvesting of the forest land (Kaboggoza, 2011). Those actions paved the way to the degraded present state of Uganda's forests and the absence of a sustainable wood supply for the local population.

In recent years the reforestation of degraded forest land and the establishment of new forest plantation has become a focus for the country. This has been motivated and supported by several development plans such as National Forestry Plan and the National Development Plans I & II. Additionally, in the face of climate change and a steadily rising population of 3,03% between 2002 and 2014 (UBOS, 2017) annually, Uganda needs a reliable wood supply through tree planting with resilient and adaptive tree species. Tree planting in Uganda has been undertaken using fast growing exotic tree species such as *Eucalyptus spp.* and *Pine* (Kaboggoza, 2011). The main purpose of these forest plantations is pulp production, timber, supply for fuel wood and poles for the electrical grid. Furthermore, focus on exotic tree species has led to abandonment of indigenous tree species such as *Croton spp., Khaya spp., and Maesopsis eminii.* Moreover, there are limited studies and scarce literature on the growth and yield of these indigenous tree species apart from CO2 storage, e.g., ECOTRUST (2017), most especially in Uganda. Therefore, the current study will focus on understanding the growth rates and yield of indigenous tree species hence contributing to fill the knowledge gap.

Figure 1Forest cover change for different management regimes (UMWE, et al., 2016)



1.2 Research Objectives

The main purpose of this research is contribute to a scientific base for a sustainable wood supply for Uganda. This will be done through the strengthening of farmers with the production capacity to plant trees species in their farms. As an outcome, farmers will have the ability to choose between different tree species in terms of their scientific approved yield and growth rates. Therefore, the farmers could stock their land with the most promising tree species available.

This will strengthen and support the further development of rural areas with the creation of employment in the forestry sector and contiguous sectors. Additionally, Uganda will be independent from wood imports and can build up the wood value-chain with suitable tree species.

Objective:

To understand and assess the growth performance of the observed tree species

Specific objectives:

I. Identify the tree species planted within the small scale forestry and farm-forestry systems

II. To estimate growth rate of selected tree species and the relationship between DBH and height of selected tree species

III. To estimate the yield of selected tree species in terms of volume per area

IV. To assess the vitality and health of the observed tree species

1.3 Scope

The scope of this bachelor thesis is on the performance of different tree species in western Uganda and more specifically in the Mubende district, Uganda.

Therefore trees were measured in farm-forestry or agroforestry systems of 20 farmers of Madudu suncounty, to gather comparable data on tree growth and the circumstances of the local tree growers and farmers.

As variables this research considered the DBH, tree height, age, length of commercial stem, second diameter measurement at a specific height, soil fertility, stem volume and the tree species itself.

The tree species which will be considered in this research are selected, for the high profile in the study area and the knowing of the age by the owner.

2 LITERATURE REVIEW

2.1 Tree species and their performance

The tree species *Grevillea robusta, Maesopsis eminii, Croton spp.* and *Ficus spp.* are considered as fast growing tree species (ECOTRUST, 2017).

Maesopsis eminii is a fast growing, pioneer (Kaboggoza, 2011) and a native tree species of Uganda. The main purpose of this tree is hardwood timber production (ibid). It prefers medium fertile, deep and well drained soils. The natural occurrence of the species is mainly in cooler, moist to wet conditions with a rainfall of 1.200 mm to 3.000 mm per year (ECOTRUST, 2017) and a temperature range between 18-24 degree Celsius (Kaboggoza, 2011). Table 1 displays the growth values of *Maesopsis eminii* in Uganda at a site index of 25 at the age 10 years (Buchholz, et al., 2010). The trials with *Maesopsis eminii* in Uganda showed a height of 12 m at the age of 5 years (Wajja-Musukwe, et al., 2008).

Table 1 Single tree management model for Maesopsis eminii for 25 SI (Buchholz, et al., 2010)

ACTIVITY	AGE (years)	HEIGHT (m)	DBH (cm)	BOLE LENGTH (m)	STAND DENSITY (N/ha)	SQUARE SPACING (m)	MEAN ANNUAL INCREAMENT (MAI) IN TIMBER VOLUME $m^3/ha/a$
Establishment	0	-	-	-	200	10	-
Thinning	5	17.1	34	8.5	100	10	13.4
-	10	25	46	12.5	50	14	13.6
-	15	31.1	54	15.5	50	14	14.1
Harvest	20	34.6	59	17.3	50	14	13.9

To the *Croton spp.* belongs for example the fast growing in high potential areas *C. megalocarpus* (Katende, et al., 1995). The main use of the wood is for timber, poles and firewood (ibid). The species are widely spread over Uganda, the presence of *C. megalocarpus* is in semi- humid mountain forest with an annual rainfall of 900mm to 1.900mm (Maroyi, 2015) and an attitude range from 1.200 m to 2.400 m *C. megalocarpus* (Katende, et al., 1995). *C. megalocarpus* develops a taproot which makes it quite drought resistant (Maroyi, 2015). Some tree reached a high of 3 m in two years and 11,5 m at an age of five (ibid).

Grevillea robusta, is originally native to Australia but planted since a long time in Uganda. *G. robusta* prefers well drained soils with a neutral to acidic ph value. It doesn't tolerate heavy clays or waterlogging (Katende, et al., 1995). The wood is mostly used for firewood, poles, timber and also furniture (ibid). Trees which were planted at Kifu, Uganda reached a height of 13 m with 5 years (Wajja-Musukwe, et al., 2008). Another example of the performance of *G. robusta* from plantations in Rwanda is shown in Table 2.

Table 2 Performance of G. robusta in plantations in Rwanda (Kalinganire, 1996)

Ecol. zone code [a]	Alt. range (m)	Age (years)	Height (m)			Diameter (cm)			Volume (m^3)
			Mean	SE	MAI	Mean	SE	MAI	
1	1250–1800	5	10.5	1.2	2.1	8.5	0.8	1.7	0.060
		7	12.7	1.5	1.8	11.6	1.3	1.7	0.135
		8	18.3	2.8	2.3	21.8	1.8	2.7	0.425
		15	17.1	3.1	1.1	17.4	2.3	0.9	0.290
2	1400–1800	6	18.4	4.3	3.1	16.2	1.2	2.7	0.230
		8	15.7	3.1	2.0	15.7	1.4	2.0	0.230
		12	15.6	7.5	1.3	12.9	1.6	1.1	0.135
3	1800–2500	7	7.6	1.0	1.1	10.6	1.1	1.5	0.090
		10	19.5	5.2	2.1	17.5	1.0	1.8	0.290
		12	15.8	1.9	1.3	16.9	1.8	1.4	0.230
		14	21.5	8.8	1.5	20.9	1.6	1.5	0.355
4	1460–1900	5	9.5	2.0	1.9	9.7	1.2	1.9	0.090
		11	21.7	5.2	2.0	33.9	2.2	3.1	0.995
		17	21.8	1.5	1.3	24.5	1.1	1.4	0.505
5	1600–2800	5	9.2	2.4	1.8	7.9	0.8	1.6	0.060
		7	13.2	0.9	1.9	14.2	1.2	2.0	0.175
		9	11.4	0.8	1.3	9.8	0.9	1.1	0.090
		17	30.1	1.0	1.8	24.2	1.7	1.4	0.505
6	1400–1800	5	15.5	3.7	3.1	12.4	1.4	2.5	0.135
7	900–1500	4	14.0	0.7	2.3	13.7	1.4	3.4	0.175

[a] Ecological zone: 1, Savannes; 2, Plateau Central; 3, Crete Zaire-Nil; 4, Lac Kivu; 5, Hautes Altitudes; 6, Impala; 7, Imbo.
SE, standard error of the mean; MAI, mean annual increment.

The following tree species were included in this research. *Markhamia lutea* belongs to the family Bignoniaceae (Katende, et al., 1995). The tree is commonly found at forest edges, pasture land, river valleys, as conclusion this tree species is well adopted to areas outside the forest (Meunier Q., 2010). This fast growing tree species can gain more than two meters per year on good sites (ibid). It grows on a wide range of soil types and depths up to 2.000 m altitude. Furthermore, it is drought resistant (ibid), but won't stand waterlogging (Katende, et al., 1995). The wood is very durable and termite resistant (ibid) it provides high quality poles and beams for construction, firewood and charcoal (Meunier Q., 2010). The most common propagation method is coppicing, the success rate is around 95% (ibid).

Ficus natalensis is a Moraceae and commonly found in Uganda and many parts of Africa. It grows in wet and dry areas, in savannas up to rainfall woodlands in an altitude up to 2.200 m (Katende, et al., 1995). The tree often starts his life as an epiphyte and becomes a strangler after a while and finally replaces the host tree (ibid), in order to this the trunk is mostly interwoven with roots. The common uses of *Ficus natalensis* in farm forestry system are for traditional bark clothes, firewood and shade for the coffee or banana plants (ibid).

Antiaris toxicaria belongs also to the Moraceae. It grows in an altitude from 1.300 m to 1.700 m (Katende, et al., 1995). The tree species is found in wooded grasslands, lower montane forest, but also in river valleys and semi-swamp forests (ibid). This specimen is an up to 50m height deciduous tree (Meunier Q., 2010), it reaches his full size after 20 to 30 years according to the site (ibid). The steam has a good self pruning ability, it grows best in forest stands where it reaches its top height of 40 m to 50 m in comparison to drier and more open sites where it rarely reaches more than 20 m (ibid). The wood is soft, light and not resistant to termites (ibid). Therefore, the use of the wood is in most cases for veneer, light construction timber or also plywood (ibid).

Artocarpus heterophyllus commonly known as Jackfruit is a Moraceae (Katende, et al., 1995). Originally it comes from western India but was introduced in Uganda around the 1940's and is now widespread over Uganda (ibid). This fruit tree needs fertile, deep and well-drained soils and is not resistant against waterlogging or droughts (ibid). The tree has multiple uses the main is for its fruits followed by firewood, furniture, as body for lorries and shade for other plants (ibid).

The Mango tree, *Mangifera indica* belongs to the family Anacardiaceae (Katende, et al., 1995). Like the Jackfruit it is original from India and cultivated in whole Uganda (ibid). The tree prefers well drained sandy-loamy soils but is not tolerant against flooding. The roots are deep and swallow to ensure a sufficient water and nutrient supply. The main uses are food, firewood, shade and as a fire break (ibid).

Psidium guajava or Guave (Myrtaceae*)* (Katende, et al., 1995) originates to south America. It grows in regions where water or rainfall is abundant around 1.000-2.000 mm annually (ibid). It doesn't tolerate waterlogging but is drought resistant. The main uses are the fruits which are a good income for the farmers and later the wood for firewood, poles or tool handles (ibid).

The last fruit tree *Persea americana* or Avocado is a part of the family Lauraceae (Katende, et al., 1995). This tree originates to tropical America and widely spreads in Uganda coastlands to montane forests, it is found in all moist areas of Uganda (ibid). If intercropped, the dense close to the surface root system competes with the other plants except beans. The main use of the tree is the fruit, firewood, charcoal and as shade for other crops (ibid).

Albizia coriaria is one of the slow growing trees found in Uganda from 700 m-1.700 m (Meunier Q., 2010). The tree species belongs to the family of the Fabaceae (Katende, et al., 1995). It is a pioneer species and grows therefore also on dry, poor and rocky soils and preferable on forest edges or wooded grassland with enough sunlight (Meunier Q., 2010). Furthermore, through its ability to fix nitrogen in the soil it is often used in agroforestry systems (ibid). The main uses of the tree are firewood, charcoal, shade and the roots and bark as medicine, the heavy heartwood is also used for furniture and veneers (ibid).

The tree species *Spathodea campanulata* (S. nilotica) or Uganda flame tree belongs to the family Bignoniaceae (Katende, et al., 1995) and is related to the *Markhamia spp.* It grows up to 35 m height (Meunier Q., 2010), but unlike to the *Markhamia spp.* it is found on forest edges instead of inside the forest (ibid). The altitude range is from 0 m up to 2.000 m, it is drought resistant for up to 6 months (ibid) and grows on a wide range of habitats. The wood is not durable, soft and is a not valuable timber (ibid). The fuelwood quality is poor, therefore the wood is widely used for plywood, carvings or ornamental (Katende, et al., 1995).

The following Table 3 shows for different tree species found in Uganda the survival rate in %, the mean height in cm after 13 months and their crown width after 13 months. The survival rate and mean height is very useful to predict the farmers effort for the establishment of the tree species.

Table 3 Survival rate and mean height after 13 months of different tree species, adjusted table after (Stangeland, et al., 2011)

Scientific name	% survival	n[a]	Mean height (cm)[b]	Mean crown width (cm)[b]
Acacia macrothyrsa (TS 214)	23.1	3	98 (36)	109 (36)
Albizia coriaria (TS 119)	75	21	64 (5)	57 (4)
Annona squamosa (TS 365)	17.4	4	74 (8)	35 (6)
Artocarpus heterophyllus (JRST 459)	80	24	127 (9)	59 (8)
Calliandra calothyrsus (TS 352)	92.9	13	257 (14)	192 (26)
Callistemon citrinus (TS 344)	73.3	22	185 (18)	112 (11)
Calpurnia aurea (TS 219)	25.9	7	125 (18)	78 (14)
Canarium schweinfurthii (JRST 538)	12.5	3	59 (11)	54 (14)
Capparis tomentosa (TS 5, 9, 10, 118)	74.1	20	47 (4)	42 (5)
Carica papaya (JRST 506)	75	12	204 (14)	203 (16)
Carissa spinarum (TS 348)	93.3	28	147 (8)	160 (7)
Ceiba pentandra (TS 202)	100	28	235 (9)	149 (8)
Entada abyssinica (TS 349)	62.1	18	129 (18)	76 (12)
Erythrina abyssinica (JRST 26)	72.4	21	75 (8)	53 (8)
Eugenia jambos (TS 204)	78.6	22	71 (4)	53 (5)
Ficus natalensis (JRST 477)	42.1	8	77 (11)	29 (7)
Ficus sycomorus (JRST 472)	92.9	26	168 (10)	127 (9)
Leucaena leucocephala (TS 360)	93.1	27	222 (12)	157 (13)
Maesopsis eminii (TS 355)	10	2	132 (52)	134 (67)
Markhamia lutea (TS 398)	93.3	28	144 (11)	82 (7)
Milicia excelsa (JRST 500)	86.7	26	108 (4)	75 (5)
Sarcocephalus latifolius (TS1, 3, 16)	96.7	29	211 (15)	264 (18)
Senna siamea (JRST 262)	92.9	26	319 (18)	257 (24)
Senna sp.(TS 362)	60	18	120 (16)	115 (19)
Senna spectabilis (TS 343)	83.3	10	409 (48)	230 (41)
Terminalia schimperiana(TS 351, 354)	100	18	155 (7)	147 (8)
Warburgia salutaris (TS 109)	42.3	11	84 (9)	63 (7)

[a] Subsamples of surviving trees

[b] Values in brackets represent SE of mean

2.2 Utilization of Ugandan trees

The uses of some main tree species cultivated by farmers in Mayuge district, Uganda is shown in Table 4. The values indicate the abundance of the different uses beneath the farmers. And how much they contribute to the income of the farmers. The low income numbers signal that most farmers use the wood and fruits of the trees for their own needs, only 7% of the farmers sell their tree products (Kyarikunda M., 2017). The farmers also told that the main barriers for investing in wood and selling it are: the late return of profit and the weak market for wood products (ibid).

Table 4 Uses of different tree species in Mayuge district, Uganda; table changed from (Kyarikunda M., 2017)

Species	Total use value	Use value by category Edible fruit	Timber	Construction poles and wood	Firewood	Income
Artocarpus heterophyllus Lam.	1.30	0.93	0.13	0.02	0.07	0.06
Mangifera indica L.	1.23	0.93	0.03		0.11	0.07
Milicia excelsa (Welw.) C. Berg	1.03	0.01	0.57	0.32	0.04	0.02
Persea americana Mill.	1.01	0.80	0.01		0.03	0.06
Maesopsis eminii Engl.	1.00		0.46	0.23	0.19	0.06
Ficus natalensis Hochst.	0.83	0.01	0.13	0.09	0.11	
Markhamia lutea (Benth.) K. Schum.	0.68		0.13	0.41	0.06	0.02
Carica papaya L.	0.46	0.40				0.03
Albizia coriaria	0.37		0.17	0.07	0.03	

The publication of (Lamoris Okullo J., 2003) shows similar findings for northern Uganda. An extract of some tree species and their uses from the research can be found in Table 5.

Table 5 Uses of tree species in northern Uganda; (Lamoris Okullo J., 2003)table changed

Tree/shrub species	*Uses*
Albizia grandibacteata	Firewood, fodder (pods), reeds
Albizia coriaria	Timber, shade, soil fertility improvement
Senna spectabilis	Poles, medicine, windbreaks and crafts
Markhamia lutea	Poles, windbreaks, crafts and medicine
Mangifera indica	Fruits, charcoal, shade and windbreaks
Ficus natalensis	Soil fertility improvement

2.3 Growth characteristic

The growth characteristics of the trees in Uganda or East Africa are characterized by the typical s-shaped sigmoid curve (West, 2009) if a specific tree variable is plotted against age on the x axis. This shape of the curve is similar for many tree species in the world. The first segment of the curves starts with a slow increase of the tree variable in the first years due to the small and developing root system (Röhle). The second phase is characterized through a strong increase in inclination of the curve, because of a developed root system therefore nutrients and water can be easily accessed. The second period with its big increment is followed by a period with little increment over age till the harvest or the death of the tree (ibid). The point where the growth rate starts to decrease in called the infection point. The yield curve before the infection point is convex and after the inflection point concave. The infection point displays also the point with the highest annual increment over age (West, 2009).

The decreasing increment in the last period is mainly because of environmental and biological reasons. Environmental reasons could be the weather, poor soil or the occurrence.

For example, trees who are growing solitary are more exposed to the wind and don't have to compete with other trees, therefore their big height increment stops earlier in comparison to trees who are growing in a tree collective. Biological reasons could be the increasing water stress in the leaves due to an increasing distance of water transportation which leads to a lower photosynthesis rate, genetics and the stability or structure of the wood (West, 2009).

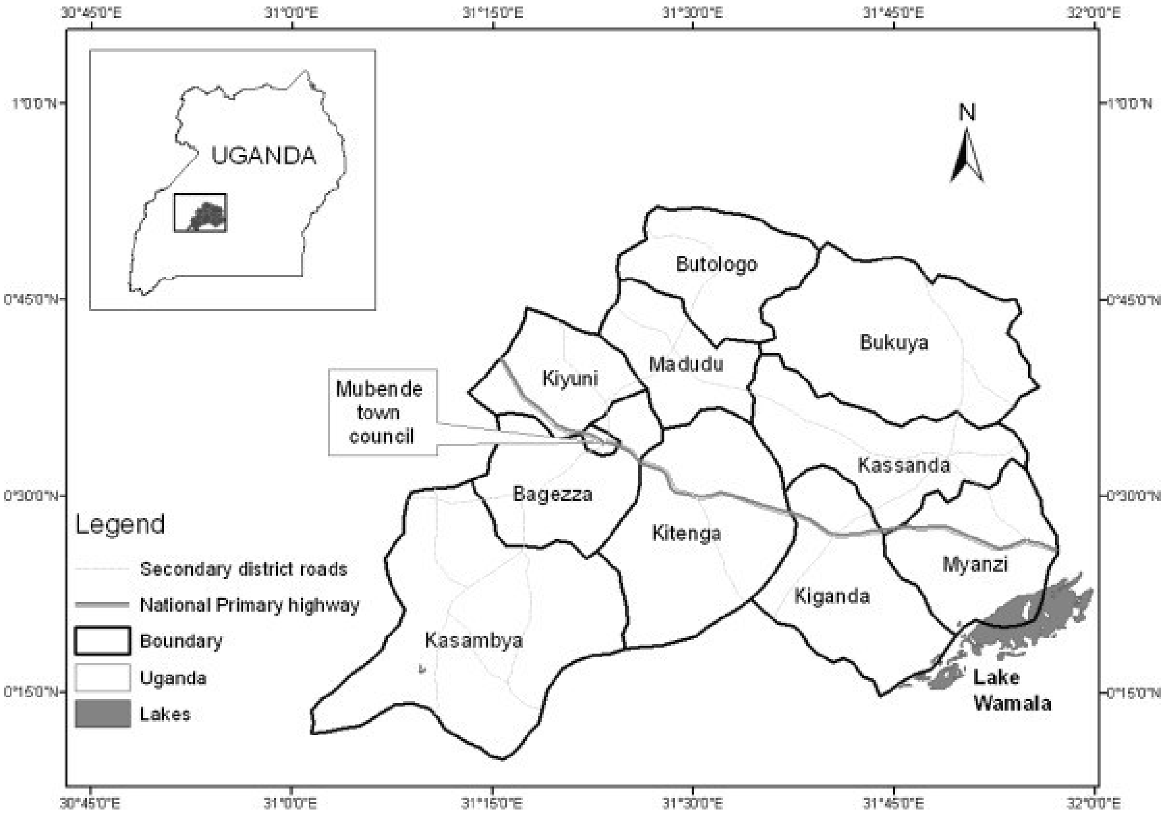
The length and the increment of the respective period is individual for every tree species e.g. fast growing tree species have a higher increment over all periods than slow growing species, or light tree species have a higher increment in tree variables then non-light trees.

3 THE STUDY AREA

3.1 Description of the Study area

Mubende district is one of the oldest districts in Uganda, covering a total area of 4646 sq. kilometers. Mubende district located in the central region of Uganda (Figure 2, upper left site; (source:

Figure 2 Map of Mubende and his subcountys



https://www.researchgate.net/figure/Map-of-Mubende-district-in-Uganda-with-the-10-sub-counties_fig2_224916746 last access: 28.2.2018)). The boarders are: in the north Kyankwanzi district, in the east Mityana district, in the south Sembabule and Gomba district and in the west Kyegegwa in Kibaale district. The government headquarters of the district are located in the district capital Mubende. Uganda has a population of 34,9 million inhabitants, 684.348 inhabitants (Uganda Bureau of Statistics , 2017) of them are living in the district Mubende.

The climate in Mubende district is tropical with a varying annual rainfall from 560 mm up to 1.272 mm (Mubende District Local Government, 2011). There are two rainy seasons, the first is from March to May and the second is from September to November, therefore Uganda possesses two growing seasons. The average annual temperature is fluctuating from 17 degrees to 29 degrees Celsius (ibid).

Mubende's altitude ranges around 1.300 m above sea level (ibid). Most of Mubende lays on a plate only in in the northern and western part of the district are small mountains which are commonly known as Mubende Hills.

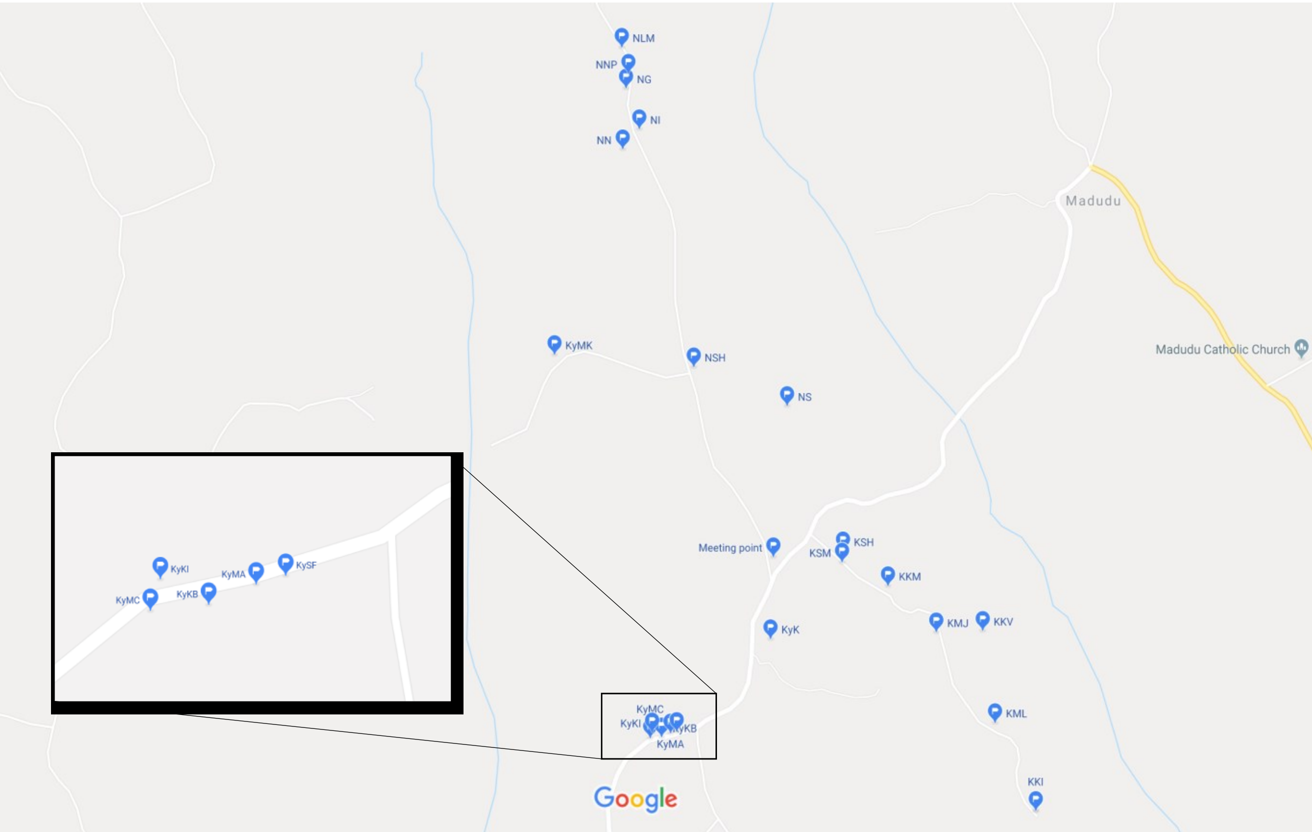
Agriculture is the biggest economic sector for the people. Over 70% of the population depends on agricultural activities such as cultivating maize, banana and cassava (ibid). The industrial sector is only present in urban areas where production sites are connected to the water and electricity grid.

Because of the high number of people depending on agriculture and its products the necessity for a sustainable managing of the land and its environmental resources is crucial. An increasing degradation of soils and the consequences of a slowly changing climate is reducing agricultural outputs. Therefore, the need arises for suitable ways of managing the land, growing crops and trees. Additionally, is the fact that over 98% (ibid) of the energy sources are covered by fuel wood and charcoal.

3.2 Farm description

For the research 20 farmers were included. All of them were located in Madudu subcounty, north-east of Mubende town. The farms stretched out over three villages Kikiyamakobe, Kyunga and Nakasozi. The following show the location of all farms with their farmcode. The farmcode is an abbreviation consisting of the villages name first, of the farmers family name second and of the farmers surname third. For example, NSH means the farm is located in Nakasozi and the famers name is Ssemiyingo Hermann. In some cases, the surname wasn't recorded, then the farmcode consists of only two letters e.g. NS means the village is Nakasozi and the farmers name Sawagna.

Figure 3 Figure 3 Location of the conducted farms with their farm codes



On all farms the trees were intercropped with either coffee, maize, beans, cassava, groundnut or banana. The approach to intercrop one year agricultural crops with woody perennials such as trees, palms or shrubs is called agroforestry (Nair, 1993). The main difference to other land uses is that on the same unit of land agricultural as well as silvicultural operations are carried out. The agroforestry system consists of an agricultural and tree subsystem. This research focus on the trees in the tree subsystem. Some impressions of the growing conditions and the kind of agroforestry approach can be found in appendix 9.1.

The soil on which the trees are growing were similar on all farms. The soil structure is a sandy clay, sandy clay loam or a clay loam which appeared the most. The ph value fluctuates between 4,5 to 6 according to the site. The soil has a yellow red color with the hue 5 to 7.5, a low value of two to three and a chroma of one to three according to the Munsell Soil Color Chart. The organic matter content is determined according the guideline from (FAO, 2006) and is situated between 3-5% in the upper soil. Those observations coincide with the data from (Jones, 2015) that the dominant soil in this research area a Haplic Ferralsol is with a dominant red color and a texture of a sandy loam.

The main purposes of the trees on the farm site is for shade, timber or firewood. Table 11 and appendix 9.10 shows the various main purposes and values of the trees. The occurrence of the measured trees where either isolated without any interferences from other branches in their crown, in a loose slightly pressed situation with branches from other trees touching each other or in row where the interference from other branches in the crown was strong. The exact growth condition of every tree can be looked up in the field sheets in appendix 9.8.

4 Material and Methods

4.1 Secondary data collection

To get a first impression of the research method and study area a literature review will be conducted beforehand. The focus will be on scientific literature and publications about forest and tree measurement and about Uganda and the vegetation. Because of the specific research area all kinds of reliable resources must be considered to get a good overview. Therefore, also internet sources and publications which are only available online in the pdf-Format will be considered in the literature review. For both sources the approach is the same: only trustworthy and scientifically approved literature will be considered for this bachelor thesis. Trustworthy sources are published books and papers as well as articles and reports from governments and organizations. The comparison of the information from one resource with another resource is vital.

4.2 Site selection

The study was conducted in Mubende district, subcounty Madudu (Figure 2 and) which is characterized by farmers.

In the research district the first task was the visiting of the farmers, to identify the trees, asking for the age of the trees and negotiate with the farmers about conducting the research in their farmland. After the identification and selection of the trees, the measurements for the thesis began.

4.3 Interviews

Throughout the research and especially during the field work interviews with the farmers will be a crucial source for information. An important role for the interviews will be the determination of the tree age, conducted silvicultural treatments, value of the tree and the purpose of the tree stand. For those interviews a default questionnaire will be used (appendix 9.2). Due to the lack of alternating growth season, tree rings in the wood are not present. The determination will be only through interviews and if existing, planting records.

Additionally, expert talks will be a reliable source of information throughout the whole bachelor thesis. Experts will be Professors, scientific staff and knowledgeable persons in their specific field of work. Notes will be taken for all expert talks.

4.4 Farm Assessments

- **Number of Farms**

The number of visited farms for this bachelor thesis is 32 farms. This number was reduced mainly because of the availability of the tree age information. According to this the number of conducted farms is reduced to 21. On these 21 farms all tree species with available age information are recorded.

- **Determination of the tree age**

The determination of the tree age is through official records or surveys among the farmers. The farmer is first questioned about the existing of age information of his trees. Secondly a visual observation of the named trees is undertaken and the measurement afterwards. If the diameter or height shows unusual e.g. very high values in comparison to already conducted trees of the same species, the farmer is interviewed again for evidence on how he could verify the tree age e.g. birth of one child in the same year of planting or first year of cultivating this land. In case the age information can't be verified, a question mark is noted additionally to the age in the field sheet. The age information is given in full years, in some cases the age information is given down to a precision of a quarter of a year.

- **Tree measurements**

The DBH is measured at 1.3m above the ground in a 90-degree angle to the stem with a diameter tape. In steep areas the DBH is measured from the hill side (West, 2009). Trees with a fork beneath the 1,3 m mark are recorded as two trees (ibid). In the case of defects or abnormalities in DBH height, two additional diameters are measured in same distance to the DBH up and down the stem summarized and divided by two afterwards (ibid).

The tree height is measured at the highest with leaves or needles greened point of the tree. The Vertex is used to measure the height, the device works with the trigonometric principles. Knowing the angles and the horizontal distance it is possible for the device to calculate the height. This measurement is conducted for all trees with given age on the farm. To ensure the correctness of the height measurements, the Vertex is regularly calibrated due to changing temperatures in the survey plots during the day.

The commercial stem length is measured with the Vertex from the ground to either the beginning of the crown, a bend or a branch which effects the end product of the stem significant.

Additionally, to the DBH a second diameter at a specific height of the tree is measured. This measurement is either at crown height or if this is out of reach the measurement is taken at a lower specific height. The height for the crown height diameter is taken from the commercial stem length. The height of the specific diameter is recorded with the Vertex, too.

- **Visual tree observations**

Additionally, for every tree the quality of the stem, silvicultural treatments, survival rate and the crown position will be collected.

The quality will be conducted in the following way through visual observation. Score 1: means the steam is perfectly straight and defect free. Score 2: stem is not perfectly straight, minor defects or high forks but at least 50% of the wood is usable for timber. Score 3: the stem has several defects, pests or diseases and major bends.

Conducted silvicultural treatments and the survival rate in % were obtained through the questioning of the farmer.

The crown position of the farm trees is divided into 4 scores. Score 0: means the tree is standing alone no interference with other trees. Score 1: means the branches of the trees touches each other. Score 2: means the tree is growing in a row, the branches of the trees intertwine more strongly and score 3: means the tree is growing in small tree stand were competition and shade have a significant effect on the trees growing performance. This will help to explain unusualness in outcomes from the data analysis.

- **Other plot-level assessments**

The coordinates of the farms are recorded through a GPS capable device.

The soil fertility and soil type are assessed to make the data of the tree stands comparable and to reduce the variance of the final growth and yield rates. Soil fertility and the soil type are classified through small on-site surveys. The soil fertility will be determined through a litmus test to gain the PH value of the soil and a description of the top H- and O- horizon to a deep of 10cm with the finger test for the soil structure and the color with the Munsell Soil Color Chart (FAO, 2006). The kind of soil is classified through soil maps and the already descripted upper horizons. Through this data the amount of organic matter can be determined cording to the guideline of (ibid). For every tree stand one 10cm deep soil pit will be dig and afterwards buried again. The soil characterization is done for every tree farm.

The data from the farm level assessments is recorded in a field sheet (see appendix 9.3).

4.5 Data Analysis

The data analysis is implemented for all tree species with more than 8 measured trees. Tree species with less observation are not considered in this research. The data of the trees with lower observation is not considered, because the measurements spread heavily in height and DBH for the few measurements over age. Moreover, some tree species are measured for only one age, which makes biological growth prediction difficult. Outliners of the data will be not considered in the regression and mentioned when not considered in the analysis. The regression analysis is conducted with the statistic program Excel. In detail it means that the sum of the squared error (SSE) of the calculated values to the corresponding observed values was minimized through the use of the solver add-in. In this way Excel is searching for values of the coefficients a, b and c that minimize the SSE of the function. The result is the minimized SSE and values for the coefficients to achieve this SSE.

Summarized the analysis follows 4 steps:

1. Checking of the gathered data and converting it into the correct form
2. Conducting the regression analysis
3. Checking of the results on plausibility and correctness
4. Plotting and describing of the results

To calculate and simulate the tree growth over the lifespan of a tree species in a limited measurement time, artificial time series are used. For artificial time series, trees in different ages with comparable growth conditions are measured. Afterwards the different measurements over age are combined to one growth series. In comparison to real time series for the tree growth were one tree is measured several times over its lifespan (long-term observations) (Pretzsch, 2009). For this analysis artificial time series are used.

- **Stand-Height-Curves**

Setting the diameter at breast height in relation to the height in a diagram and a regression analysis is conducted, a function which describes the Diameter-Height relationship is obtained. The Stand-Height-Curve will be conducted for every tree species alone. The Stand-Height-Curve displays the characteristics of the height increment over the DBH increment (Pretzsch, 2009). With this curve trees that are just measured in DBH the height can be read off the diagram. For the Diameter-Height relationship the following functions were used Michailoff equation [1], parable 2nd grade [2] and the Petterson function [3].

$$h = a * e\frac{-b}{d} + 1{,}3 \text{ [1]}$$

$$h = a + b * d + c * d^2 \text{ [2]}$$

$$h = 1{,}3 + (\frac{d}{(a+b)*d})^3 \text{ [3]}$$

Those function include the variable h for tree height and d for DBH. The coefficients a, b and c are parameters. The independent variable is d and the dependent variable is h. The used functions have been proven useful for regression analysis in Diameter-Height-Relations according to (Schmidt, 1969). The parable 2nd grade was already used by Assmann (1943) and can be used according to (Pretzsch, 2009) in selection forest and virgin forest. The Petterson function (1955) has been proven useful for even aged and single-layered stands (ibid).

- **Volume**

The tree volume V of the tree species is calculated through the use of the variables: DBH and the tree height h. The variables need to be in the same unit for the calculation. The form factor f is a factor. To compute the single tree volume of the trees the following equation is used:

$$V = \Pi * \left(\frac{DBH}{2}\right)^2 h * f \text{ [8]}$$

This equation is the volume equation for a cylinder, with the addition of the form factor f. The form factor can be seen as a reduction factor for the cylinder to obtain the conical volume of the tree stem. For the form factor in equation [9] the value 0,4 will be used for all tree species. The form factor 0,4 is selected to rather underestimate the volume of the trees than to overestimate it and propose to high incomes for the farmers. This form factor is also recommended by FAO for tree species with no existing form factors or local equations (FAO, 2005).

The result of this volume equation is the volume of the tree from the bottom to the top of the tree.

- **Yield functions**

Yield functions are used to describe observed tree dimensions e.g. volume, height, DBH over age, in growth models to predict the yield of trees and tree stands or to measure the effect of disturbances on the growth. According to this the ability of extrapolation of the yield function needs to be ensured. The used yield functions can be applied for DBH, tree volume or tree height increment (Pretzsch, 2009). The difference between growth and yield functions is, growth functions display the growth per year of height, DBH or volume in mean annual increment (MAI) or current annual increment (CAI), whereas the yield function display the sum of CAI at a certain age. Growth functions are the derivate of yield functions. The outcome of this regression includes correct and reproducible height curves and tree volume curves of the tree species.

- **Height curve functions**

The height curves are based on the tree height and age. The indicator for the height curve is meter, the dependent variable is the tree height and the independent variables is the age. For this regression the equations Bertalanffy [4], Champman-Richards [5], Gompertz [6] and Levakovich III [7] are used.

$$h = a * (1 - e(-b * age))^3 \text{ [4]}$$

$$h = a * (1 - e(-b * age))^c \text{ [5]}$$

$$h = a * e(-b * e(-c * age)) \text{ [6]}$$

$$h = a * \frac{age^2}{b + age^2}^{c} \text{ [7]}$$

The variables are h for the calculated tree height and age. The parameters are a and b for all functions and additionally c for the last three functions.

The Bertalanffy function [4] and [9] is the only function which uses 2 parameters. The infection point is fixed through the exponent of 3 in comparison to [5] or [10], where the parameter c the flexibility of the infection point ensures. According to (Pretzsch, 2009) the most used yield function is the Champman-Richards function [5] and [10], which is also used in the growth simulator SILVIA. The Richards function is also mentioned as an applicable function for tropical forests (Vanclay, 1995). Through the three parameters a, b and c the asymptote, slope and the coordinates of the infections point can be controlled (ibid). This allows the curve to be fitted to a wide range of data. The backside of the flexibility is the loss of biological plausibility (ibid). According to (Pretzsch, 2009) Kiviste and Zeide argue that the yield functions of Levakovich III [6] and [11], Gompertz [7] and Hossfeld IV [12] used for modelling tree volume, achieve higher levels in biological plausibility (ibid) in comparison to the Richardson function.

- **Tree volume function**

The tree volume functions are based on the volume as dependent variable and age as independent variable. The tree volume functions are calculated for every tree species with the following four functions Bertalanffy [9], Champman-Richards [10], Levakovich III [11] and Hossfeld IV [12].

$$V = a * (1 - e(-b * age))^3 \ [9]$$

$$V = a * (1 - e(-b * age))^c \ [10]$$

$$V = a * e(-b * e(-c * age)) \ [11]$$

$$V = \frac{age^c}{b + age^c/a} \ [12]$$

The function [9] uses two parameters a and b whereas the last three functions always use three coefficients a, b and c. The variable age describes the age in years and V describes the volume.
The Hossfeld IV [12] is not commonly used for modeling but according to (Pretzsch, 2009) it still achieves the same accuracy as the Richards equation for height and diameter growth and is preferably used for modelling tree volume growth (ibid).

- **DBH functions**

The DBH curve is included in this research to make it convenient for the farmer to check if their trees are growing slower or faster as the average. Convenient because the farmer only needs a diameter or

measuring tape to measure the DBH of the tree and not an expensive and scare available height measurement device.
For the modelling of the DBH curves only the Richards function [13] is used for all tree species. This is because of the reason that this function is providing biological plausible and statistical good curves.

$$DBH = a * (1 - e(-b * age))^c \ [13]$$

The structure of the function is exactly the same as in [5] or [10]. The only minor difference is that now the DBH is the dependent variable.

- **Interview**

The prices for one timber or one pole are given in Ugandan Schilling (UGX) and Euro (€) for the year of selling. Additionally, in an extra column adjusted with the inflation rate between the year of selling and 2018. The inflation rate is used to make the prices from different years comparable.
Two reductions of the calculated tree volume are undertaken. The first reduction is undertaken to gain the merchantable volume of the tree. To calculate this value the reduction rate of two thirds is chosen through the author. This ratio is used firstly because of the over bark diameter measurement, which could lead to a reduction of the tree volume of up to 20% (Röhle). Secondly, because of the small diameters in the upper section of the stem, which are to small for timbers. The second reduction of the merchantable volume will be made through the conversion efficiency of the chainsaw. The conversion ratio of the timber is 40% after the study (Nketiah, 2004) which was conducted in Ghana. The ratio varies with the skill of the cutting the person, kerf width, sawing patterns and market demands (ibid).
The conversion efficiency of the chainsaw is used through the absence of a sawmill in the research area and the availability of chainsaws through timber buyers.
Based on the calculated prices for one timber in 2018 an upscaling to monetary single tree and hectare values is made. Through that a projection is made for a possible extra income of the farmer through the cultivating of the trees in an agroforestry system. The projection is made for a rotation period of 20 years. Through the upscaling of the interview data from single tree monetary values to ha values, comparable and competitive monetary values are the result.

2.4 Statistical values

To determine a regression analysis a variety of indicators can be used to describe the precision of the regression line. The most important and for this analysis used the sum of squared error, the standard of estimate and the coefficient of determination will be used (Pretzsch, 2009).

The sum of squared error (SSE) is the sum of the squared results of the observed data minus the predicted data. The SSE describes the deviation of the observed data to the predicted data.

The standard error of estimates (SEE) is the square root of the division of SSE by the number of observations. The SEE can be seen as a measurement of the accuracy of the prediction.

The coefficient of determination (R^2) is the total sum of squares divided by residual sum of squares. The numerator describes the residuals of the regression (observed minus predicted data) and the denominator the variance of the data to its mean. R^2 can attain values between zero and one. Assumed that the data of the regression analysis would match perfectly on the observed data, R^2 would be zero.

The biological plausibility should be also equally taken into account in the process of selection the most suitable function (Pretzsch, 2009).

4.6 Research Limitations

The data acquirement is the sector with the biggest chance of mistakes or uncertainties. The biggest possibility to get inaccuracy in the data will be the age determination, top height measurement and the DBH measurements. The age determination can be only as precise as the farmers will remember. The precision of the age is recorded down to a quarter of a year. The second inaccuracy will be minimized through practical experience and the data acquirement through only one person.

The frequently mentioned inaccuracy by the DBH measurement is already reduced to a minimum through the usage of a measure tape instead of a caliper.

Those actions will be undertaken to reduce uncertainties and blurring of the research data. Moreover, the reproducibility and accuracy of the research will be enhanced.

5 Results

5.2 Tree growth

This research includes 31 tree species, a list with their scientific and local names can be found in appendix 9.4. For two of the conducted tree species the scientific name couldn't be identified, this affects three measurements of 292 measured trees in all. Eight of them, namely *Markhamia lutea, Ficus* *natalensis, Mangifera indica, Artocarpus heterophyllus, Anitaris toxicaria, Persea americana, Albizia coriaria* and *Spathodea campanulata* were measured more than nine times. For those eight tree species a calculation of the DBH-Height-Relation, the height curve and the single tree volume curve is undertaken. The statistical calculations and coefficients for every tree species and function can be found in appendix 9.5.

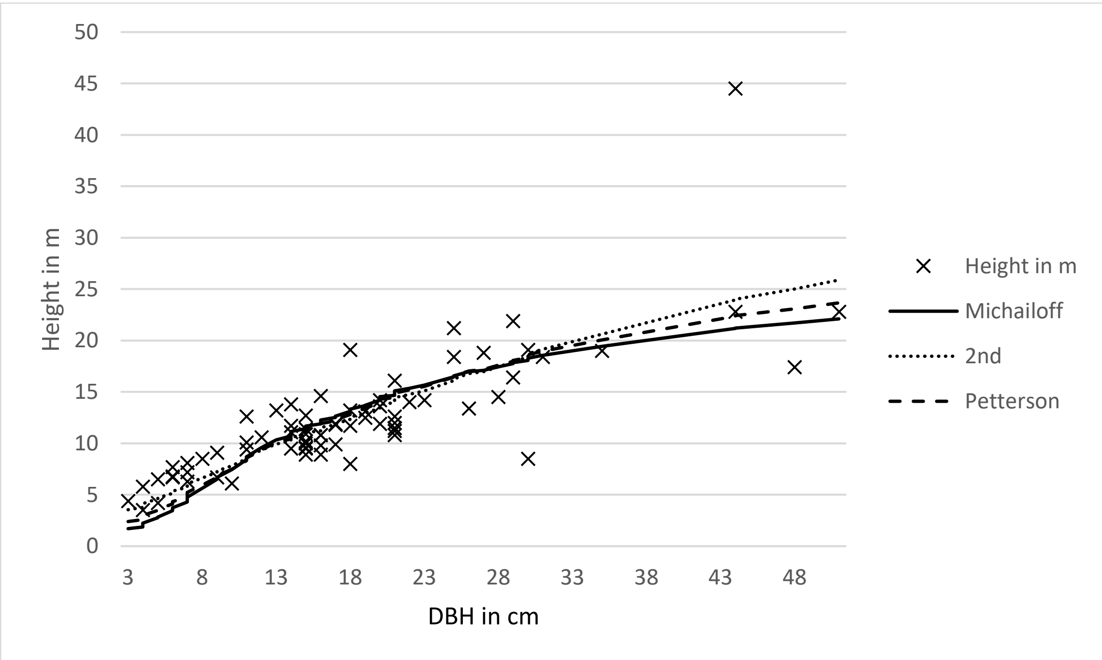
For the tree species *Markhamia lutea, Ficus natalensis, Anitaris toxicaria* and *Albizia coriaria* the Diameter-Height-Development diagram is shown first followed by the height development diagram and the tree stem volume development diagram. The curves of the other four tree species can be found in appendix 9.6. The DBH curve for all tree species can be found in chapter 5.3 Comparison of the selected curves.

In every diagram the observed heights, DBH's, or calculated volumes will be displayed as black crosses. An example of a filled-out field sheets can be found in appendix 9.8.

Markhamia lutea

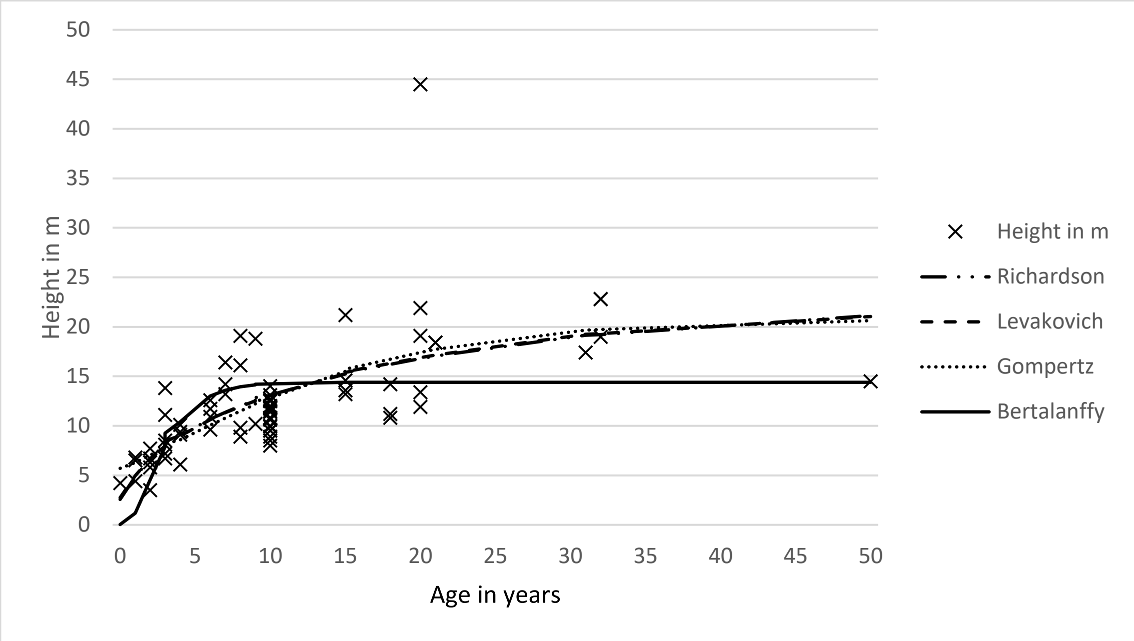
All Diameter-Height-development functions of *Markhamia lutea* reach a height of 16 m by a DBH of 25 cm (chart 1). The curves only differ in the young years between one 15 years and again between 35 years up to 50 years.

chart 1 Diameter-Height-Development of Markhamia lutea



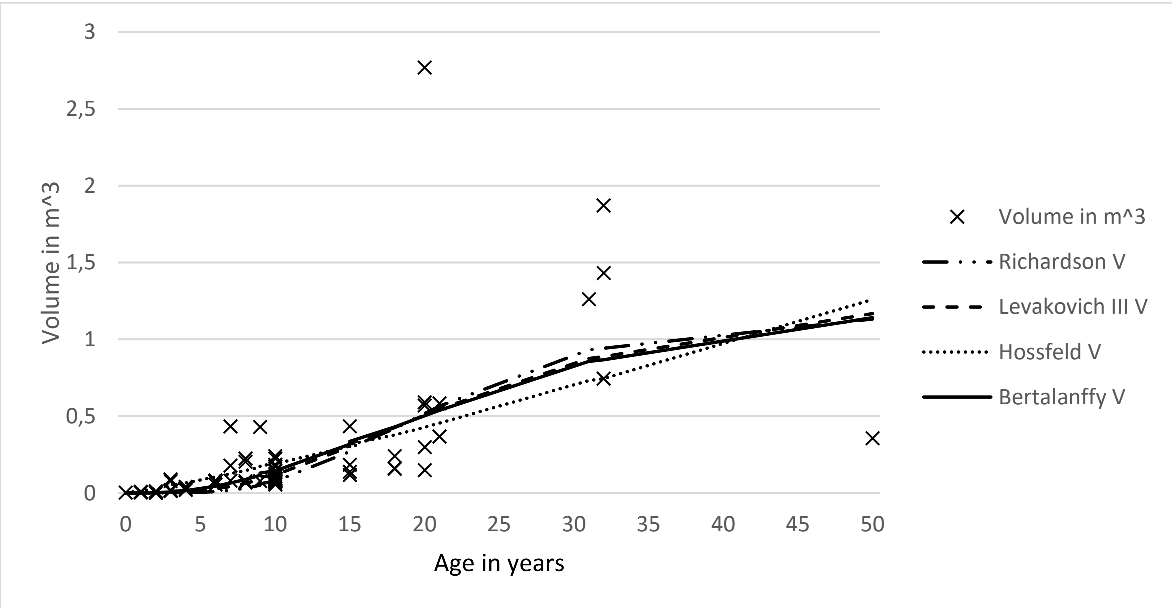
According to the calculated heights *Markhamia lutea* reaches a height between 14 m and 17,5 m in the age of 20 years (chart 2). All *Markhamia lutea* curves flatten down remarkable in comparison to the young years between 30 and 50 years, especially the Bertalanffy function.

chart 2 Height development of Markhamia lutea



The yield curves for the single tree volume of *Markhamia lutea* have the similar s shape except the Hossfeld equation chart 3. The Richards equation achieves in this case the highest R^2. The highest single tree volume in the age of 20 is not considered in the analysis. The outliner at the age of 20 wasn't considered in the analysis.

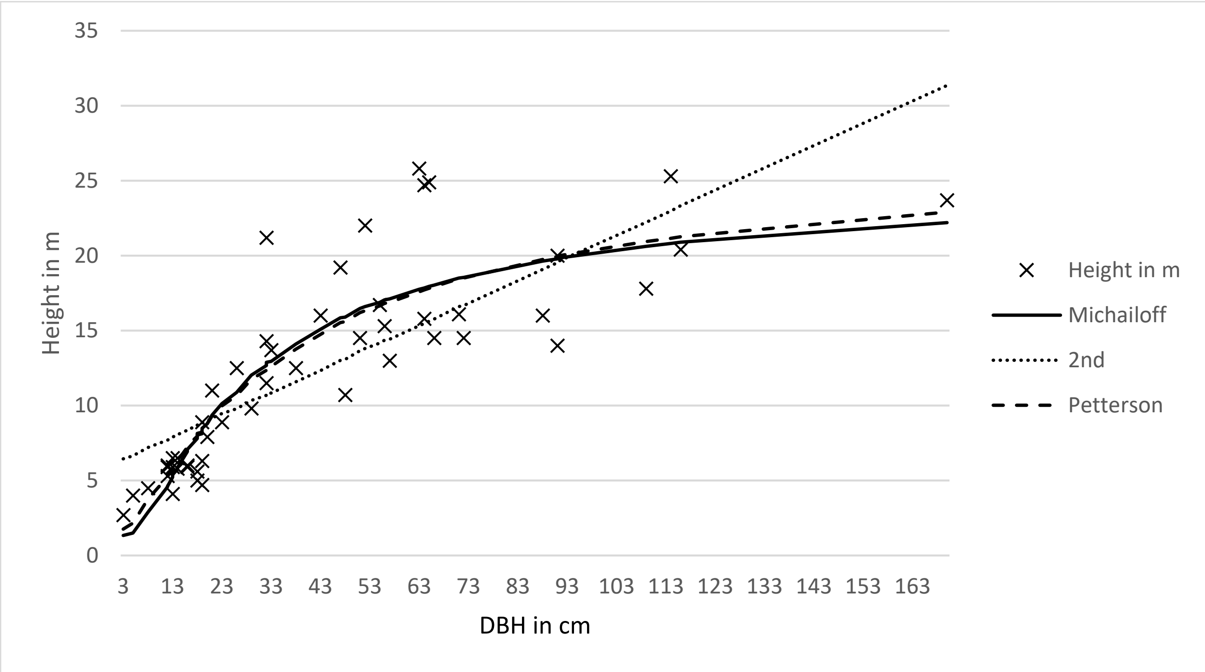
chart 3 Tree stem volume development of Markhamia lutea



Ficus natalensis

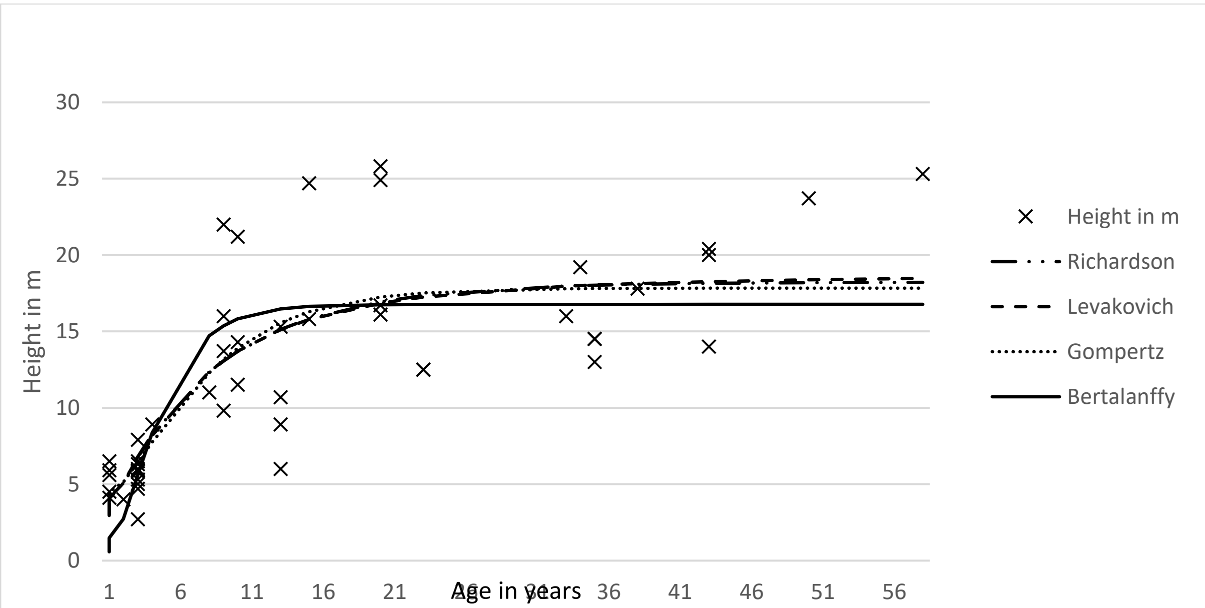
The three functions used for the Stand-Height-Curve intersect first at a DBH of 25cm and later on 95cm again (chart 4). The Michailoff and Petterson function are quadratic shaped and biological plausible in comparison the parable 2nd grade is linear consequently the coefficient c of this function is zero and therefore not biological plausible.

chart 4 Diameter-Height-Development of Ficus natalensis



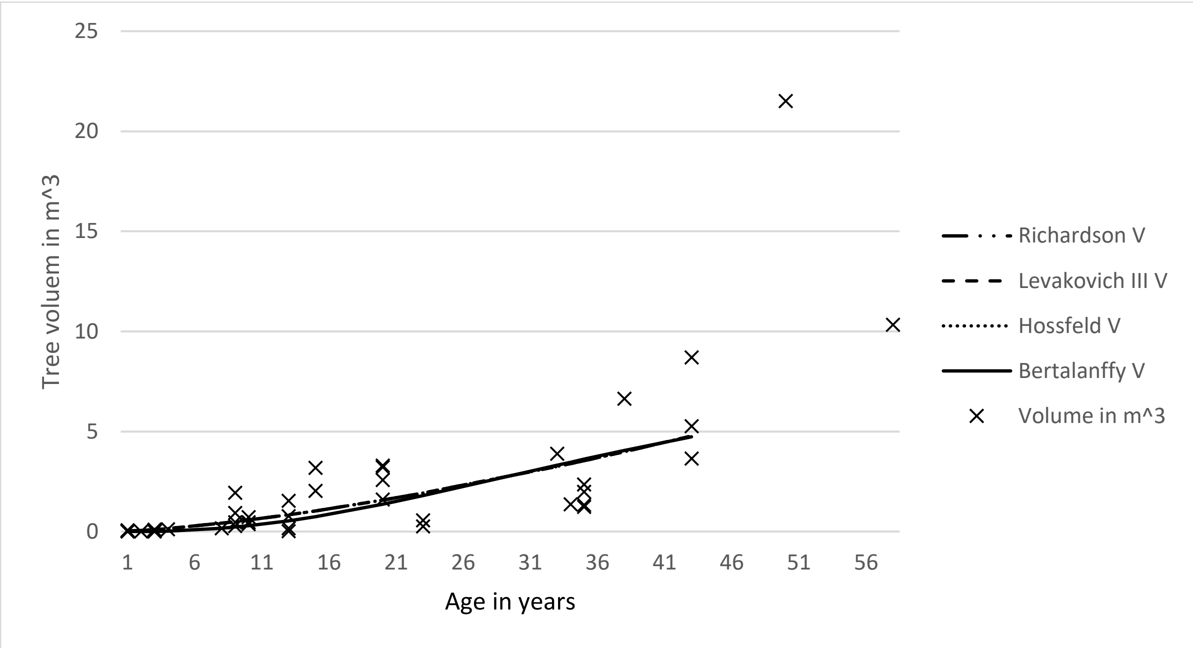
The height growth of *Ficus natalensis* in farm forestry systems is the strongest in the first 10 years, decreases strongly in the following 10 years and remains on the same low level of growth for the next 30 years. The Bertalanffy function shows again the biggest increase in the first years and flattens down as first on a level of 16,8 m, whereas the other three functions still increase up to 18,5 m (chart 5).

chart 5 Height development of Ficus natalensis



The Richards function has the typical s shaped yield curve and also achieves the lowest statistical errors and the highest R^2. The two outliners of the age 50 and 58 years were not included in the regression analysis.

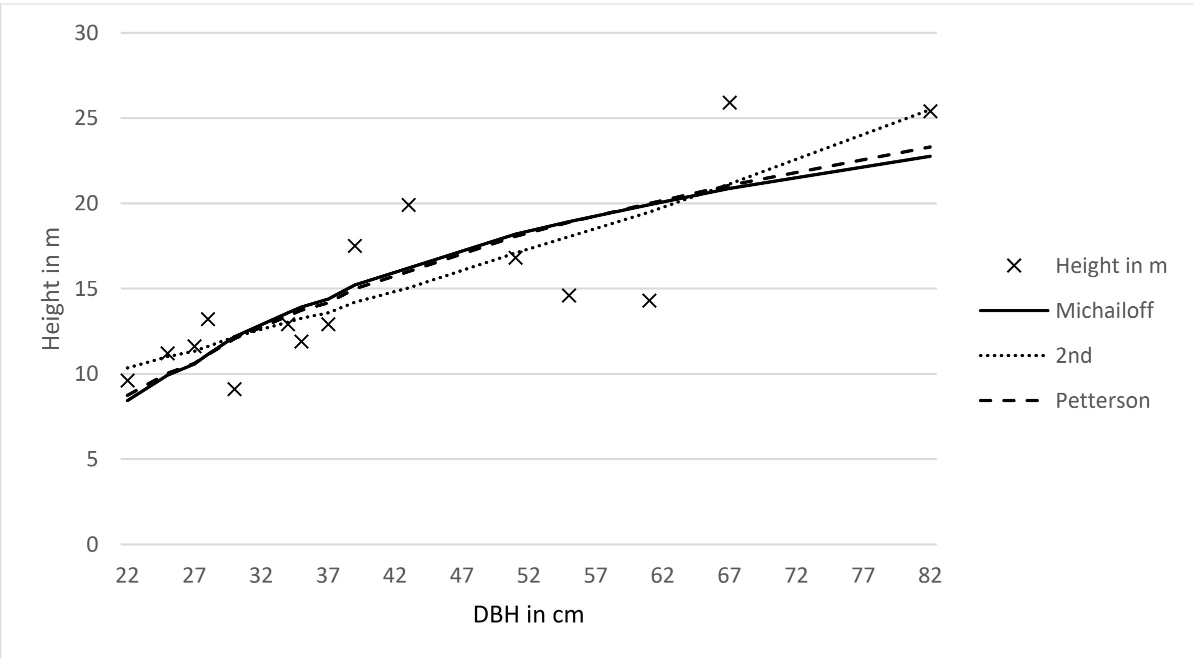
chart 6 Tree stem volume development of Ficus natalensis



Anitaris toxicaria

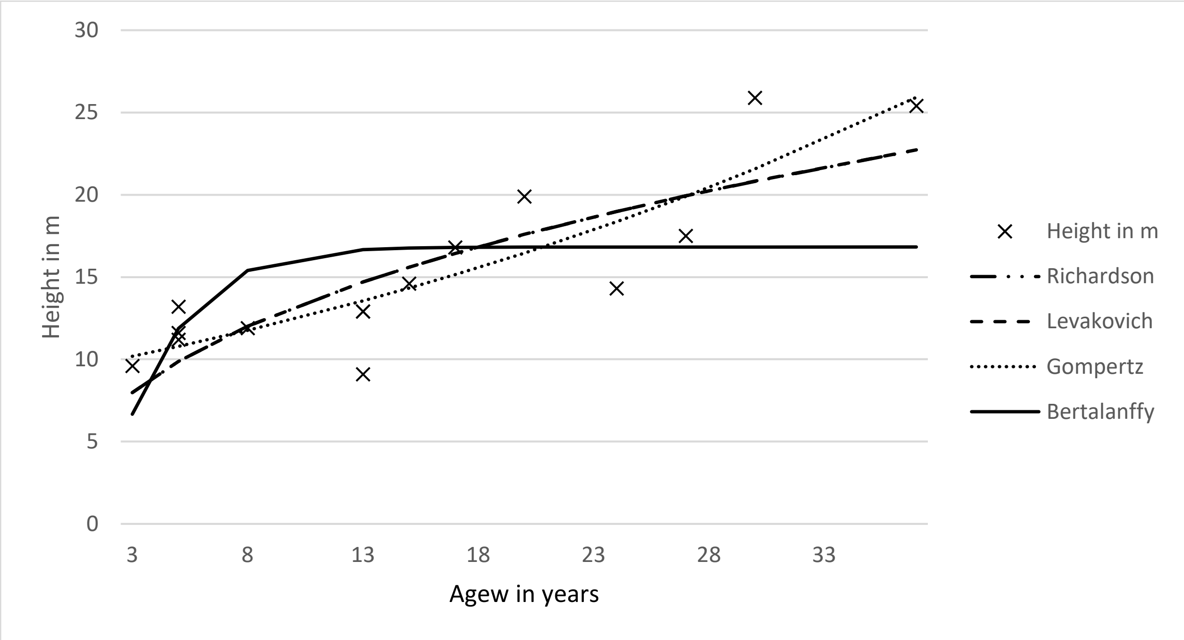
Anitaris toxicaria reaches a height of 10m to 11m at a DBH of 25cm (chart 7). Petterson and Michailoff display the best biological curves whereas the parable reaches the lowest least square in the regression analysis.

chart 7 Diameter-Height-Development of Anitaris toxicaria



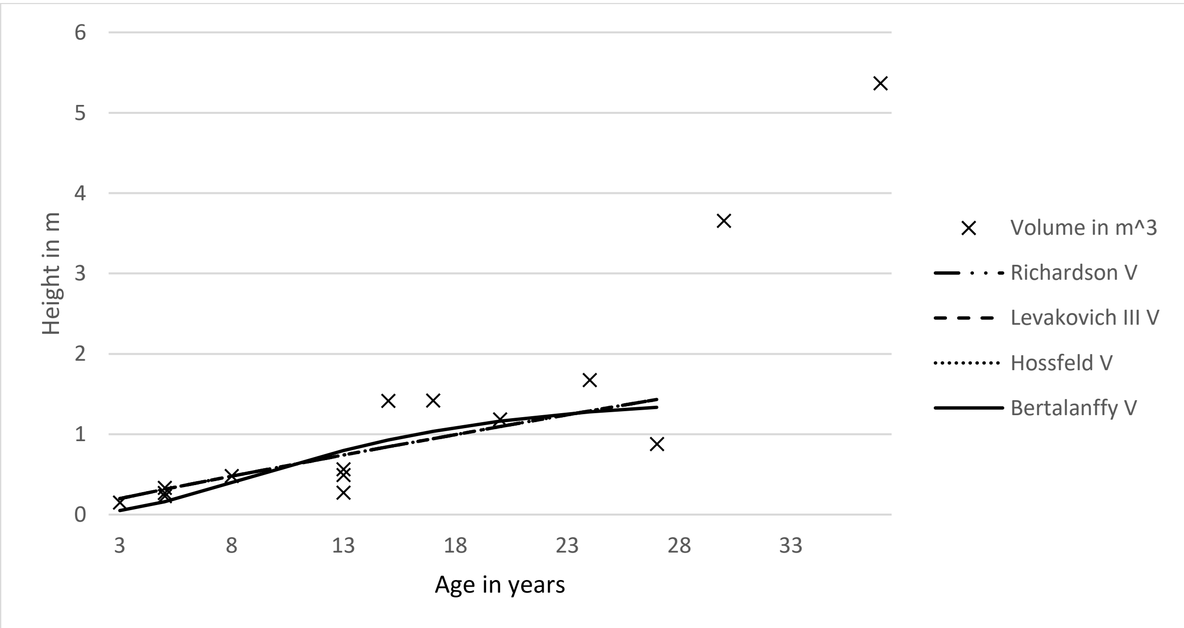
The same applies for the Stand-Height curve. In this case the Gompertz functions achieves the lowest least square value but is also at the same moment not biological plausible (chart 8). Bertalanffy shows a biological plausible curve, but also got the highest least square value.

chart 8 Height development of Anitaris toxicaria



The Richards function for *Anitaris toxicaria* is not suitable for the analysis. The other function from Levakovich, Hossfeld and Bertalnffy display comprehensibly and biological curves chart 9. Two outliner in the age of 30 and 37 years were not included in the regression.

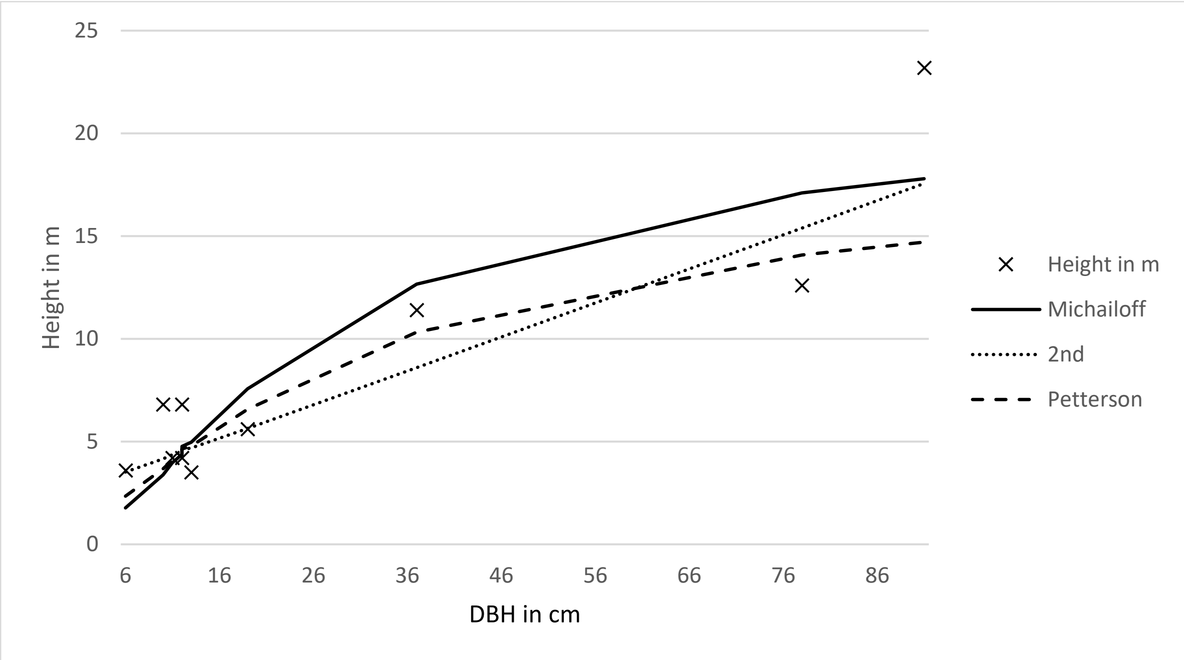
chart 9 Tree stem volume development of Anitaris toxicaria



Albizia coriaria

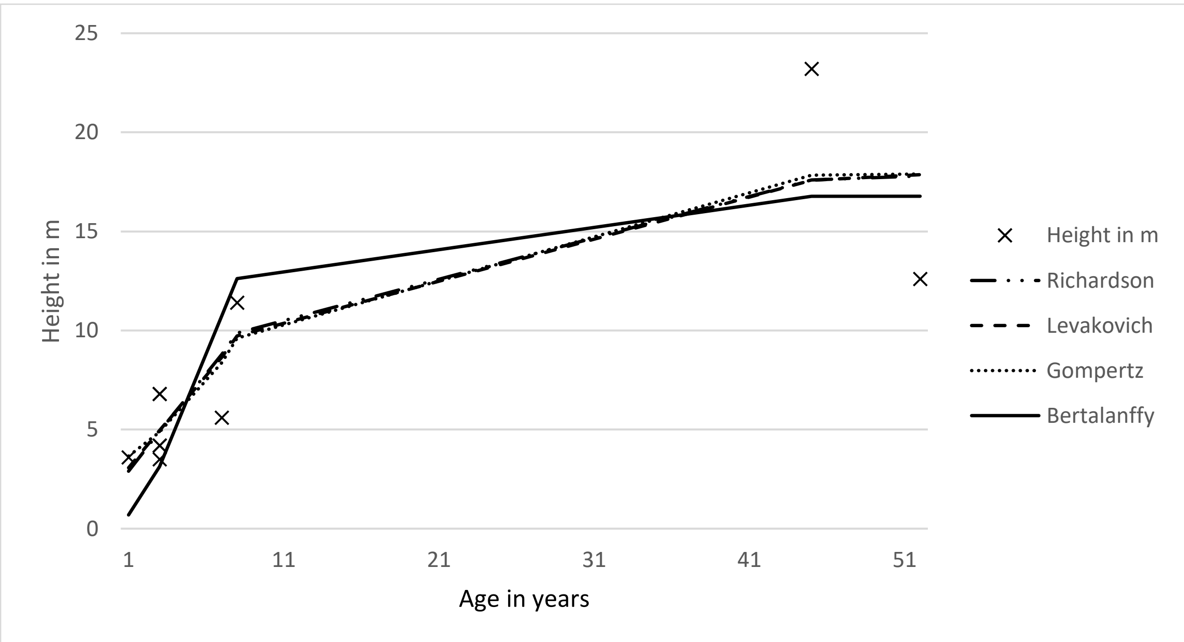
Michailoff and Petterson display a biological function with a slow decrease in the height growth in comparison to the DBH (chart 10). The Petterson function probably underestimate the height development over DBH for *Albizia coriaria*.

chart 10 Diameter-Height-Development of Albizia coriaria



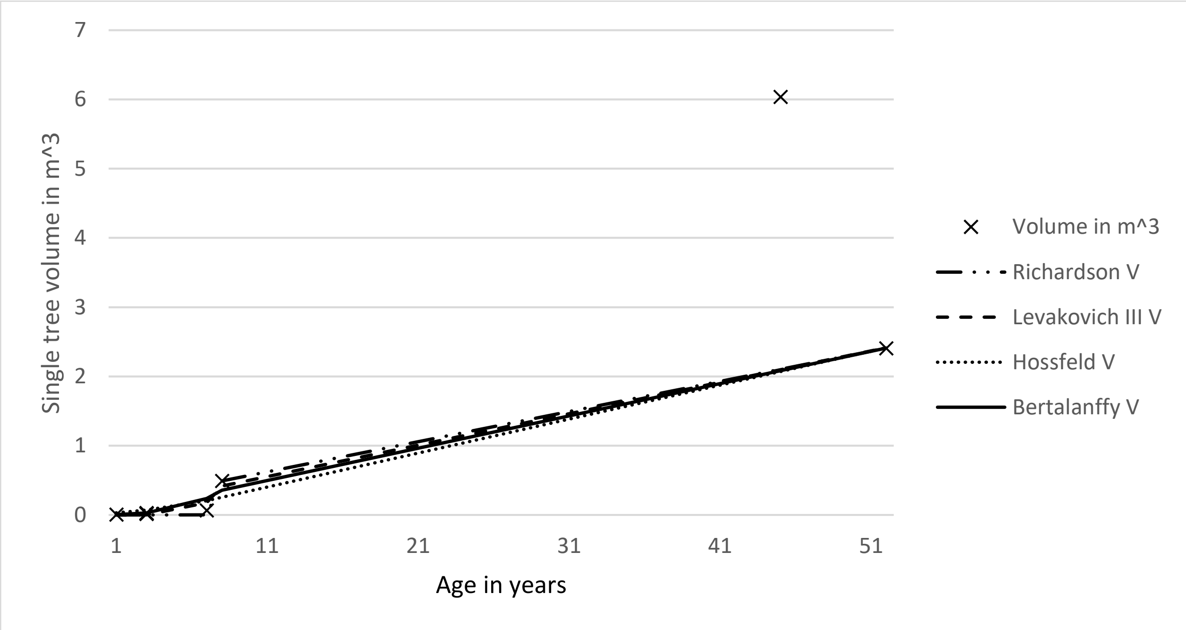
The height of *Albizia coriaria* at age of 20 ranges from12m for the Richards, Levakovich and Gompertz function to 14m for the Bertalanffy function (chart 11).

chart 11 Height development of Albizia coriaria



For the volume regression the outlier in the age of 45 years was not considered. The suitable yield curves for *Albizia coriaria* are Richards and Levakovich with a similar R^2 and biological plausibility. The functions of Bertalanffy and Hossfeld didn't lead to a scientific reliable result.

chart 12 Tree stem volume development of Albizia coriaria

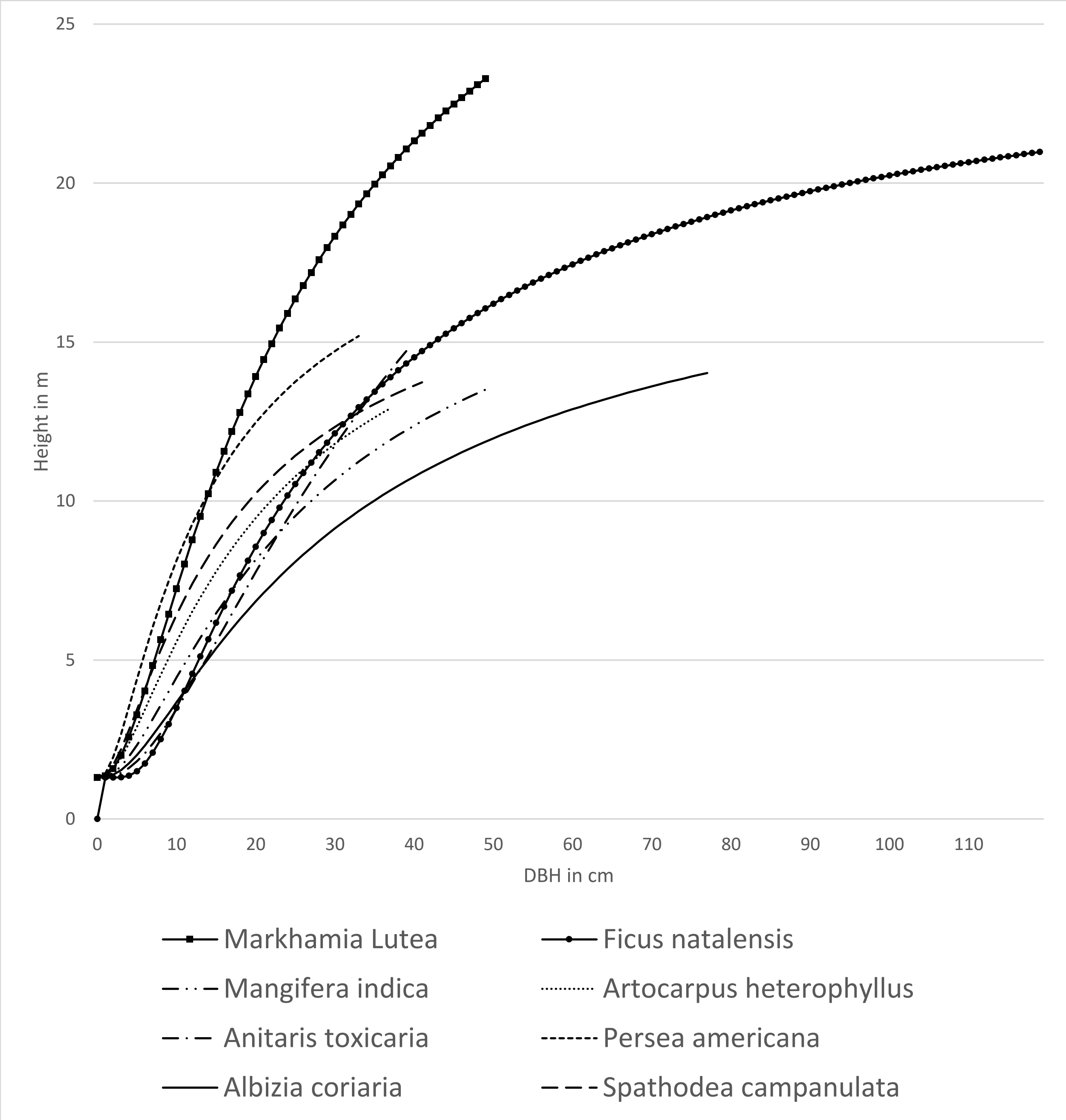


5.3 Comparison of the selected curves

The selected functions for each tree species are plotted together in one Diameter-Height-Development diagram, Height and DBH development and tree stem volume development diagram. Each diagram is followed by one chart with the calculated coefficients of the selected function and their statistical calculations. The shown curves are plotted for the observed data of the trees and are not extrapolated. The extrapolated curves can be found in appendix 9.7.

The selection was made on the prior descripted criteria, furthermore all of the selected curves show non-linear correlation and no decrease in height with bigger diameters. *Markhamia lutea* has the highest Diameter-Height-Development with a height of 23,5m at a DBH of 50cm. In comparison the lowest Stand-Height-Curve has *Albizia coriaria* with a height of 12m at a diameter of 50cm. The second tallest curve belongs to *Persea americana* till a diameter of 65cm and for the last 35cm *Ficus natalensis* achieves the second highest curve.

chart 13 Diameter-Height-Development of the selected functions



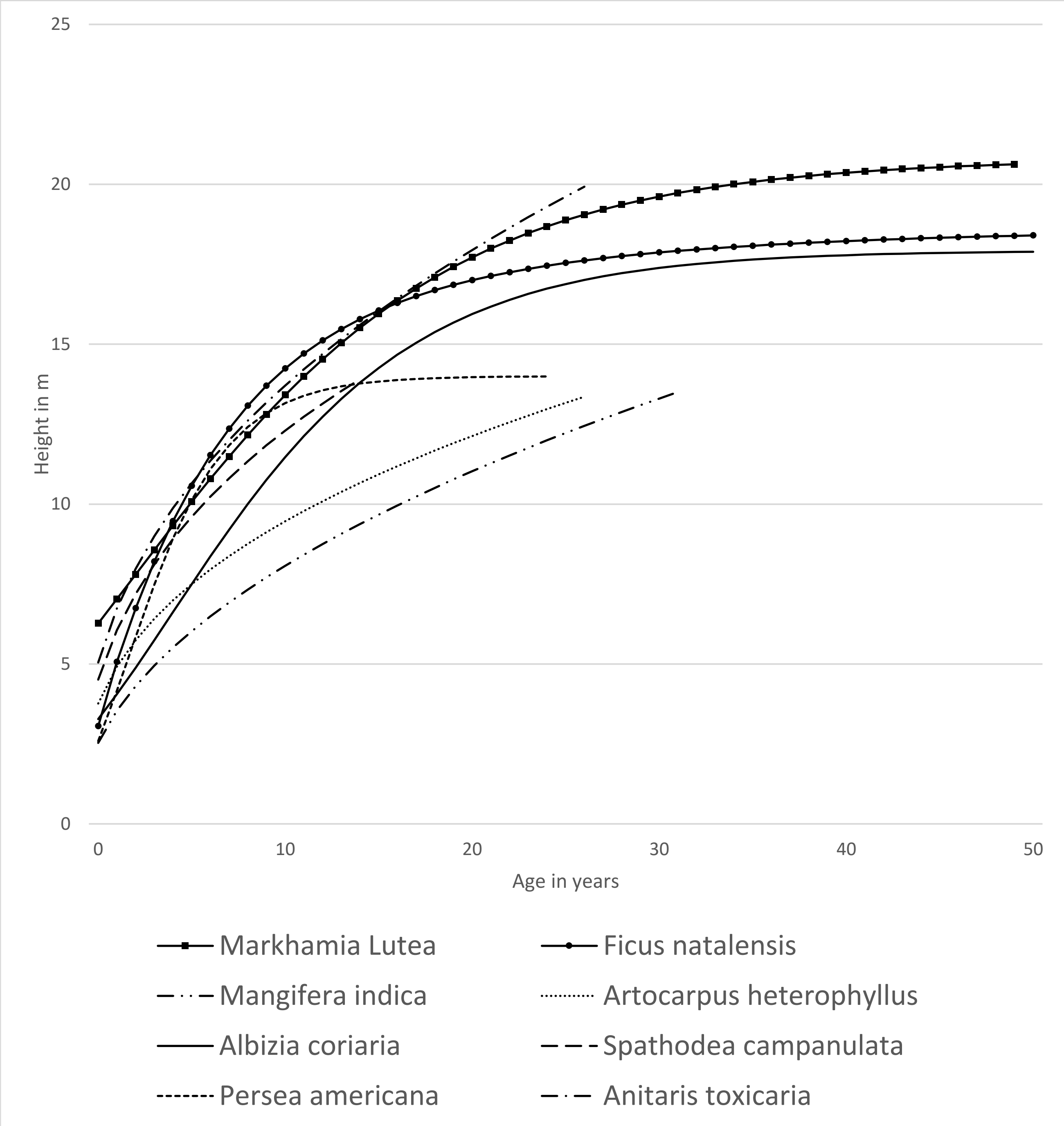
Of the three different functions which were used for the Stand-Height-Curve the parable 2nd grade achieves most often the highest R^2 but the Petterson function was in seven of eight cases the best compromise between biological plausibility and the calculated statistical values. Table 6 shows the tree species with their most suitable and selected function Stand-Height-Curve.

Table 6 Statistical values and coefficients of the selected functions

Markhamia Lutea		Anitaris toxicaria	
Petterson function	h=1,3+(d/(2,453593043+0,306905352*d))^3	Petterson function	h=1,3+(d/(4,76091362+0,298797202^d))^3
SSE	979,47	SSE	122,95
SEE	3,69	SEE	2,86
R^2	0,61	R^2	0,67
Ficus natalensis		Persea americana	
Michailoff function	h=24,06572676*EXP((-23,96182182/d)+1,3	Petterson function	h=1,3+(d/(1,59383974034005+0,367723579*d))^3
SSE	507,9045154	SSE	97,02
SEE	2,655979929	SEE	2,73
R^2	0,767	R^2	0,49
Mangifera indica		Albizia coriaria	
Petterson function	h=1,3+(d/(3,114817578+0,370795672*d))^3	Petterson function	h=1,3+(d/(3,694463,69446554554+0,380355007*d))^3
SSE	75,60	SSE	95,52
SEE	1,59	SEE	3,09
R^2	0,83	R^2	0,79
Artocarpus heterophyllus		Spathodea campanulata	
Petterson function	h=1,3+(d/(2,393865318+0,376904052*d))^3	Petterson function	h=1,3+(d/(1,963740903+0,383760142*d))^3
SSE	131,50	SSE	45,99
SEE	2,29	SEE	2,26
R^2	0,44	R^2	0,54

The selected and plotted height curves for the tree species can be found in chart 14 for a better comparison of the different curves. Four of the eight curves have a similar shape with a great increase in height in the first years between zero and ten and a slightly weaker increase in height in the years from ten to 70 chart 14. The other four curves of *Albizia coriaria, Persea americana, Markhamia lutea* and *Ficus natalensis* have a similar shape in the first ten years, but a rapid decreasing height growth per year after ten which ends in steady line.

chart 14 Height development of the tree species for the selected functions



The comparison of the selected curves and their height increment over age with other commonly used tree species in Uganda is shown in Table 7. For the comparison the tree species *Eucalyptus grandis* ("Individual Growth Model for Eucalyptus Stands in Brazil Using Artificial Neural Network, 2013), *Maesopsis eminii, Grevillea spp.* and *Croton spp.* were used.

Table 7 Specific heights of the measured trees in comparison with Maesopsis e., Eucalyptus g., Grevillea spp. and Croton spp.

	Markhamia Lutea	Ficus natalensis	Mangifera indica	Artocarpus h.	Anitaris toxicaria	Persea americana	Albizia coriaria	Spathodea c.				
age	Gompertz	Levakovich III	Richards	Richards	Richards	Gompertz	Gompertz	Richards	Maesopsis e	Croton spp.	Grevillea spp	Eucalyptus g.
5	9,3	5,5	5,5	7,0	10,4	8,9	6,6	8,9	15	12	11	24
10	12,8	7,7	7,7	9,1	12,8	12,8	10,8	11,8	25		17	30
20	17,4	10,8	10,8	11,9	15,6	14,0	15,7	15,5	35			
30	19,5	13,1	13,1	13,9	17,6	14,0	17,3	18,0			25	
50	20,6	16,8	16,7	16,9	20,3	14,0	17,9	21,4				
75	20,8	20,4	20,3	19,8	22,8	14,0	17,9	24,0				

It is clearly to see that the calculated heights don't reach the growth rates of *Maesopsis eminii, Croton spp., Grevillea spp. or Eucalyptus grandis* Table 7*. Anitaris toxicaria, Markhamia lutea* and *Spatodea campanulata* are the measured tree species which grow the tallest over their life span. The fruit trees *Mangifera indica, Artocarpus heterophyllus* and *Persea americana* have the smallest height increase over the age.

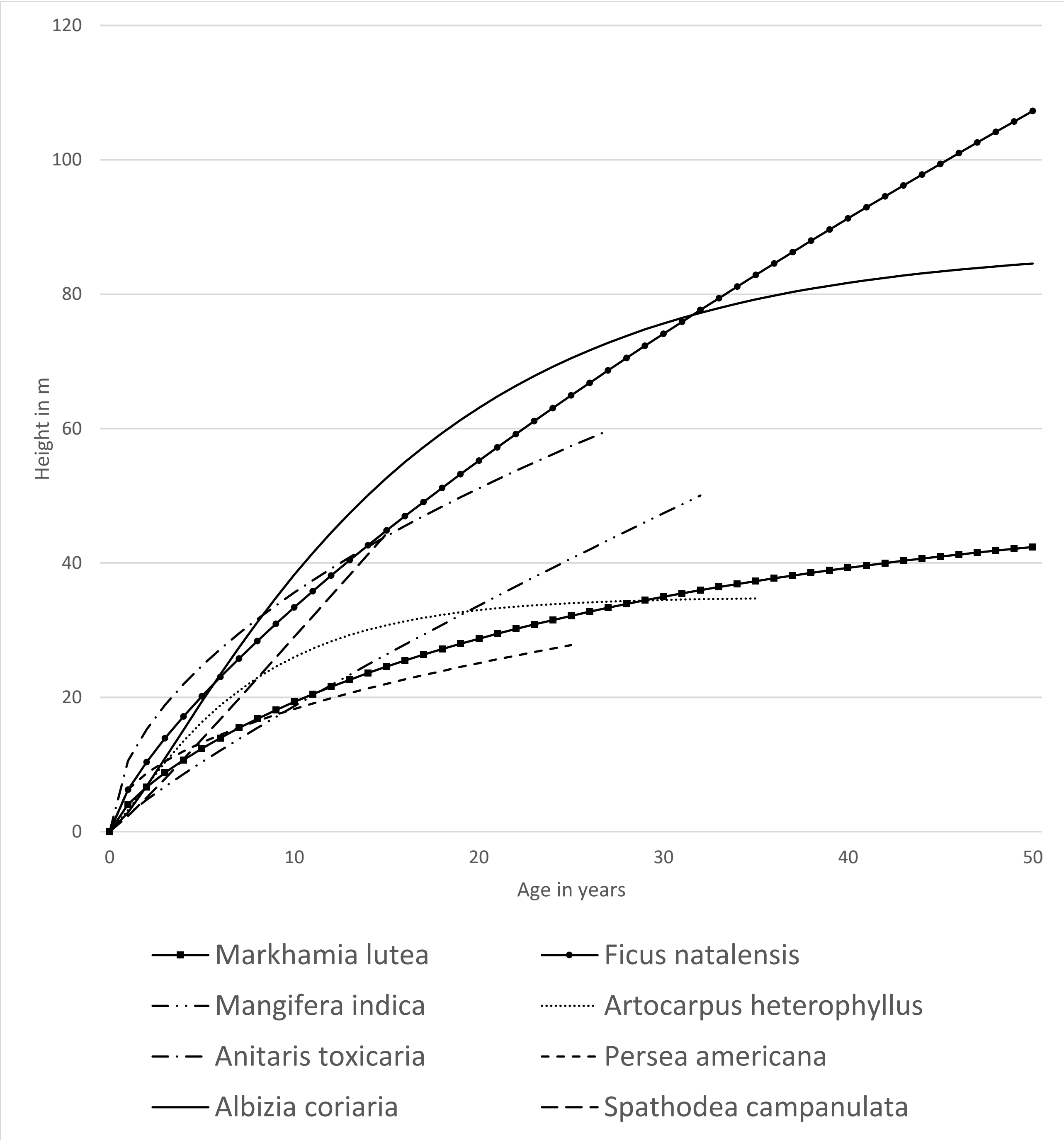
Table 8 Statistical values and coefficients of the selected height curves

Markhamia Lutea			Anitaris toxicaria	
Gompertz function	h=20,80587307*EXP(-1,326669067*EXP(-0,100477071*age)		Richards function	h=239,8392588*(1-EXP(-9,48632E-05*age))^0,416846224
SSE	1362,60		SSE	123,49
SEE	4,35		SEE	2,87
R^2	0,44		R^2	0,67
Ficus natalensis			Persea americana	
Levakovich function	h=18,74504239(age^2/(133,0538894+age^2))^0,370417354		Gompertz function	h=13,99986296*EXP(-2,346785062*EXP(-0,330035343*age)
SSE	802,3800588		SSE	71,60
SEE	3,338288107		SEE	2,35
R^2	0,631		R^2	0,62
Mangifera indica			Albizia coriaria	
Richards function	h=112,006115*(1-EXP(-0,000396724*age))^0,483774021		Gompertz function	h=17,92821087*EXP(-1,942187892*EXP(-0,133595658*age)
SSE	101,38		SSE	77,81
SEE	1,84		SEE	2,79
R^2	0,73		R^2	0,77
Artocarpus heterophyllus			Spathodea campanulata	
Richards function	h=103,5790387*(1-EXP(-0,000180257*age))^0,384461463		Richards function	h=29,82734441*(1-EXP(-0,012326023*age))^0,429006663
SSE	134,99		SSE	57,17
SEE	2,32		SEE	2,52
R^2	0,61		R^2	0,43

Table 8 displays the height functions, their coefficients and the statistical values. For the height calculations the Gompertz function achieves seven times the highest R^2 in comparison to the other functions (appendix 9.5) but is only three times the chosen function which is justified by the growth characteristics. Richardson was the most often selected function for the height curve but had only once the highest R^2. The function of Bertalanffy was neither selected or achieved a result for R^2 which should be taken in to account.

The DBH curves show two characteristic curves. The curves of *Ficus natalensis, Spathodea campanulata* and *Mangifera indica* show a nearly linear increase of DBH over age. The other curves show an exponential shape with a higher increase in DBH in the first 15 years and a weaker increase in the age from 20 years and above. *Albizia coriaria* has the strongest DBH increment till the age of 20 years for the tree species.

chart 15 DBH development of the Richards function for the tree species



The coefficients and statistical values can be found in Table 9. Remarkable is the high R^2 value for *Albizia coriaria*, even with outliers.

Table 9 The coefficients and statistical values for the DBH curves

Markhamia Lutea		Anitaris toxicaria	
Richards function	y=50,68000108*(1-exp(-0,030167673*x))^0,717195398	Richards function	y=274,3677891*(1-exp(-0,002157642*x))^0,531037775
SSE	1952,35	SSE	980,72
SEE	5,21	SEE	8,09
R^2	0,73	R^2	0,77
Ficus natalensis		Persea americana	
Richards function	y=2383,512343*(1-exp(-0,000284492*x))^0,727970155	Richards function	y=114,7370795*(1-exp(-0,001933712*x))^0,464612565
SSE	13682,44	SSE	337,35
SEE	13,79	SEE	5,09
R^2	0,77	R^2	0,54
Mangifera indica		Albizia coriaria	
Richards function	y=925,6916236*(1-exp(-0,001048719*x))^0,855385878	Richards function	y=87,0915212*(1-exp(-0,075999743*x))^1,306592624
SSE	1435,50	SSE	206,01
SEE	6,92	SEE	4,54
R^2	0,83	R^2	0,98
Artocarpus heterophyllus		Spathodea campanulata	
Richards function	y=34,89459876*(1-exp(-0,154969651*x))^1,23243339	Richards function	y=430,2892643*(1-exp(-0,009262885*x))^1,112584878
SSE	964,12	SSE	171,29
SEE	6,21	SEE	4,36
R^2	0,64	R^2	0,87

The single tree volume curves shown in

chart 16 of *Ficus natalensis, Spathodea campanulata, Artocarpus heterophyllus* and *Mangifera indica* got the same exponential shape, *Ficus natalensis* achieves the highest single tree volumes of up to 10,7 m^3 at the age of 75 years. In comparison the s-shaped curves of the other four tree species achieve a maximum volume of 2,5 m^3 for *Albizia coriaria*. Concerning the biological plausibility of those curves the last four s-shaped curves are more plausibly than the first of *Ficus natalensis, Spathodea campanulata, Artocarpus heterophyllus* and *Mangifera indica.*

chart 16 Tree stem volume development of the selected functions for the tree species

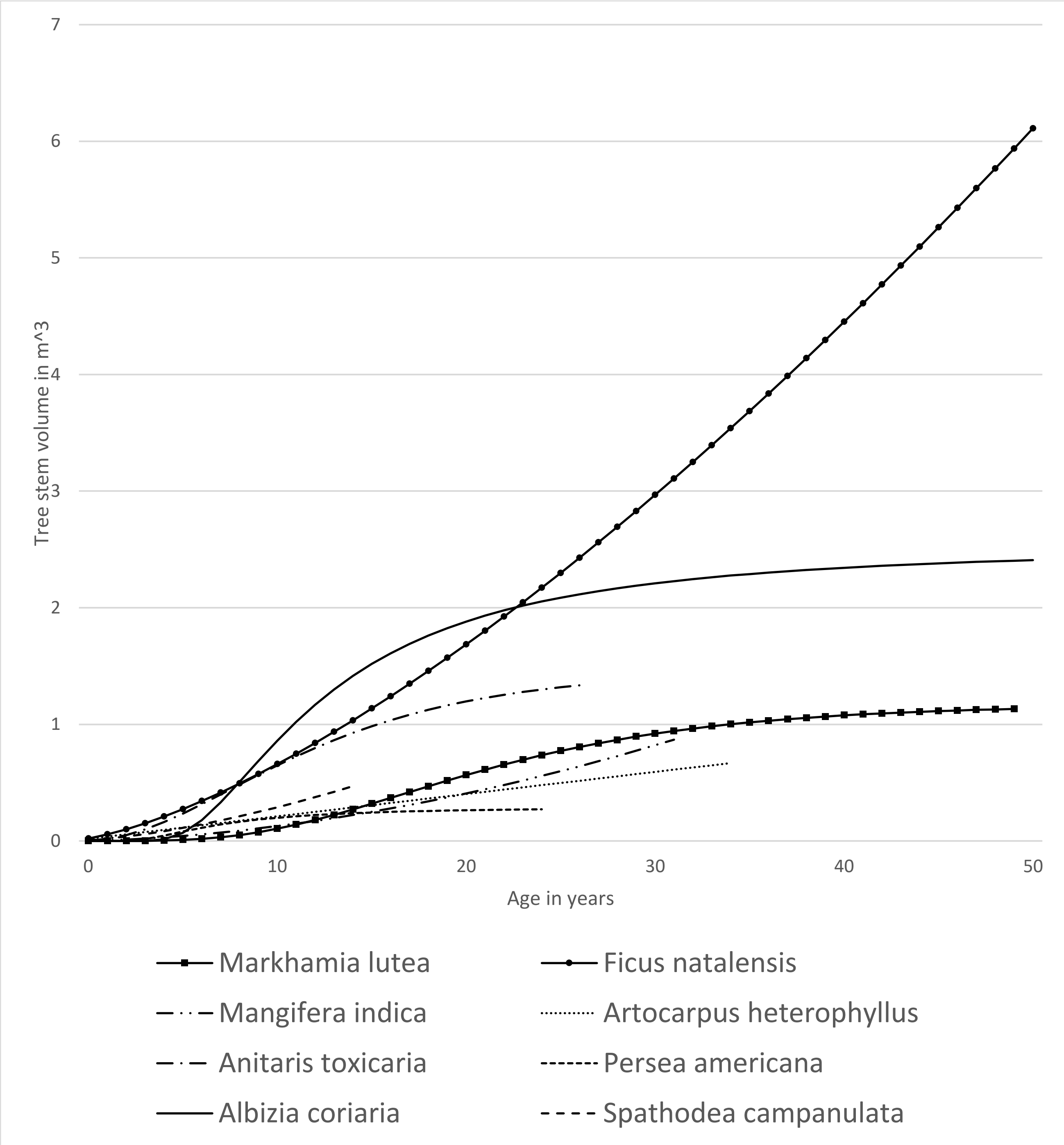


Table 10 shows the calculated and selected tree volume functions. It is recognizable that the Richards function is selected four times in comparison to the other. Bertalanffy and Hossfeld is selected once and Levakovich twice.

Table 10 Selected tree volume functions with their statistical values and coefficients

Markhamia Lutea		Anitaris toxicaria	
Richards function	V=1,166852905*(1-EXP(-0,107739958*age))^6,604005513	Bertalanffy function	V=1,458293345*(1-EXP(-0,130960143*age))^3
SSE	7,64	SSE	67,55
SEE	0,33	SEE	2,12
R^2	0,452	R^2	0,640
Ficus natalensis		Persea americana	
Richards function	V=15,71622732*(1-EXP(-0,146983415*age))^354,5577493	Levakovich function	V=0,2922838*(age^2/(0,066528216+age^2))^697,976221
SSE	63,60	SSE	0,15
SEE	0,94	SEE	0,11
R^2	0,000	R^2	0,446
Mangifera indica		Albizia coriaria	
Richards function	V=26655,78934*(1-EXP(-0,000100321*age))^1,799014662	Levakovich function	V=2,532808073*(age^2/(1,012290561+age^2))^129,6857804
SSE	0,70	SSE	6,91
SEE	0,15	SEE	0,83
R^2	0,763	R^2	0,996
Artocarpus heterophyllus		Spathodea campanulata	
Richards function	V=24,91866126*(1-EXP(-0,000789216*age))^1,004547774	Hossfeld function	V=age^1,596851638/(148,7063508+age^1,596851638/381,8807841)
SSE	0,91	SSE	0,02
SEE	0,19	SEE	0,05
R^2	0,534	R^2	0,856

Additionally, the extrapolation of the Diameter-Height-Development curves, height, DBH and tree stem volume development will be calculated in order to predict heights and volumes in higher ages. The extrapolation to an age of 75 or a diameter of up to 200cm is done for the best fitted and most biological plausibly curve of the tree species and can be found in appendix 9.7.

5.3 Interview results

The interview is completed 27 times for 11 different tree species an extract of the interview for the utilization and value of the wood is shown in Table 11.

The main purpose of the tree varies mainly with the tree species itself, its habitus and its wood characteristics. *Markhamia lutea* and *Anitaris toxicaria* have a tall and narrow habitus with a long branchless stem therefore they are mainly used for timber, poles and construction wood. The habitus of *Ficus natalensis and the fruit trees Mangifera indica, Persea americana* and *Artocarpus heterophyllus* is more like a ball or bell with low forks and a wide crown with the main use for firewood and shade.

The different utilizations can be sorted into three main objectives. One objective is building which includes timber or boards, roofing, poles and fencing. The second is cooking which includes fruits, shade for crops, fuelwood and charcoal and the third objective is tradition which includes traditional bark clothes, medicine, ornamental and preserving the environment. Through the separating of the uses it is clearly to see that the main use over all tree species is for building, second for cooking and last for traditional uses.

In Table 11 the prices are shown for one timber in UGX and € in the year of selling and in the last column in € adjusted with the inflation rate to make it comparable to present prices of 2018. The prices for one board refer to the end product, the farmer doesn't have to harvest the tree or cut the board out of the stem.

This work is under taken by the buyer of the board. The dimensions of the boards differed between 7 feet x 1 feet x 1.5 inch (2,1 m x 30 cm x 4 cm) and 12 feet x 1 feet x 1.5 inch (3,7 m x 30 cm x 4 cm). The volume of the smaller board is 0,025 m^3 and for the longer board it is 0,044 m^3. Due to the few interviews it was not possible to identify different prices for the short and long boards. The price span displays the results of the interview given by the farmers. The table is sorted by wood price starting with the highest. The used exchange rate is 1 UGX are 0,00023 €.

Table 11 Utilization and timber prices for selected tree species

Tree species	Utilization	Wood price for one board in UGX at time of selling	Wood price for one board in € on selling date	Wood price span for one board at present prices in €
Albizia coriaria	4 timber, 3 charcoal, 2 fuelwood,	8000-15000	1,76-3,3	1,8-3,3
Markhamia Lutea	4 roofing, 3 timber, 3 poles, 2	2000-10000	0,44-2,2	0,44- 2,2
Ficus natalensis	3 timber, 3 shade, 3 bark clothes,	1500-5000	0,52-1,32	0,6-1,3
Anitaris toxicaria	4 timber, 3 fuelwood, 2 shade, charcoal, barkclothes	500-5000	0,12-1,2	0,12-1,3
Muboga		5000	1,5	1,70
Sapium ellipticum		600	0,13	0,13
Artocarpus h.	fuelwood, charcoal, fruits			
Cupressus lusitanica	fuelwood, charcoal, fencing,			
Moringa oleifera	medicine, shade, preserve the			
Mubooloo	fuelwood, charcoal, blits			
Senna spectabilis	timber, poles, roofing, shade			

The values for other tree species weren't known by the farmers, because of the different main purpose of the trees. A summary of the interviews for the different tree species can be found in the appendix 9.10 and an example copy of the original interviews in appendix 9.9.

Table 12 shows the single tree volume for all tree species in m^3 and the possible hectare values for the tree species in the age of 20 years. As reference age 20 years was chosen because the volume increment of the tree species reduces significant after the age of 20 years. Additionally, it shows in the fourth and sixth column the number of long boards this volume could bear. Additionally, a reduction to the merchantable volume of two thirds and the conversion efficiency of the chainsaw cutting is included, the resulting volumes are listed in the column three. For the hectare volumes a planting of the trees in a 10 m by 10 m spacing is assumed. The table lists the tree species and their volume starting with the highest volume.

Table 12 Single tree stem volumes, merchantable tree volume and hectare volumes

Tree species	Volume of one tree at 20 years in m^3	Merchantable volume of the tree in m^3	Number of big boards out of one tree at age of 20 years	Harvest volume for one hectare at age of 20 years in m^3	Number of big boards from one hectare at the age of 20 years
Albizia coriaria	1,9	0,50	11	190	1140
Ficus natalensis	1,7	0,45	10	170	1020
Anitaris toxicaria	1,2	0,32	7	120	720
Spathodea c.	0,9	0,24	5	90	540
Markhamia lutea	0,7	0,18	4	70	420
Artocarpus h.	0,4	0,11	2	40	240
Mangifera indica	0,4	0,11	2	40	240
Persea americana	0,3	0,08	1	30	100

In Table 13 just the four species with known board prices and calculated volume curves are shown. The Table 13 shows the maximum extra income for the farmer after 20 years and the theoretical annual extra income for the farmer. The annual income is shown to make it more comparable to annual crops. The maximum values are based on the highest price complied by the interview and refers to big boards. The hectare values are based on a tree planting with the spacing 10 m by 10 m, which equals 100 trees per hectare. Noted that the calculated income in this case don't include silvicultural costs and only refers to the wood value and not to the additional value of the fruits. The table starts with the highest income after 20 years.

Table 13 Possible incomes out of the cultivation of trees in agroforestry systems

Tree species	Number of big boards out of one tree at age of 20 years	Max. value in € for one tree	Max. ha income in € after 20 years	Max. yearly ha income in €
Albizia coriaria	11	36,3	3630	181,5
Ficus natalensis	10	13	1300	65
Markhamia lutea	4	8,8	880	44
Anitaris toxicaria	7	9,1	910	45,5

As an explanatory example of the table, a *Markhamia lutea* tree in the age of 20 would have a volume of 0,7 m³, after the calculated Richards curve. In this example, the tree could provide 4 long boards after the volume reductions. This would be an extra income of 40.000UGX for the farmer in the harvesting year for one tree. Assumed that the farmer would plant one ha with 100 *Markhamia lutea* trees in a 10 m by 10 m spacing, this would be an extra income of 140.000 UGX (880 €). The annual extra income could be 44 € additionally to the income of the agricultural operations e.g. coffee with an annual return of 530€ to 1.150€ for one ha in Mubende (Hillinger, 2018).

Noted that the trees could increase the income of farmers and contribute positive to the growing conditions of planted agricultural crops by consistent farm size. Specially, for the intercropping with shade needing crops the benefits for an intercropping with trees is overweighting. The income could also decrease slightly, e.g. if a *Ficus natalensis* is intercropped with more sun needing crops. In the end the preference of the farmer decides which tree he intercrops, and which crops are cultivated beneath the tree trees.

7 Discussion of methods and results

A pre-selection on the tree species could ensure a more satisfying and reliable data collection, through more observations for one tree species.

The measurement method could be improved through a tool which is able to measure diameters in different heights without climbing the tree. Climbing a tree is a time consuming, dangerous and often not possible operation.

For the used Stand-Height-Curves the parable 2nd grade achieves in seven of eight cases the best statistical results but has at the same time a low biological plausibility because of a linear correlation. In juvenile years a linear correlation is possible due to big height and DBH increments. But a linear correlation is not plausible for higher DBH's, every tree reaches somewhen its maximum height but not its maximum DBH. This stop in height growth can be through genetic or environmental factors.

The Bertalanffy functions always flattens down very early after a significant height increase in the first 10 to 15 years and has therefore a low coefficient of determination. This is probably to the fact of the power to three. Other functions like Richards avoid this drawback through the third coefficient. In order to avoid this drawback, the Richards function gains in flexibility, but also loses in biological plausibility. The function of Levakovich, Gompertz or Hossfeld were originally chosen for the regression to bring in functions with another structure that could possible lead to other curves. Contrary to the expectations, they had sometimes the same shape as the Richards or Bertalanffy function, therefore an analysis with other functions which will be developed for such growth conditions could lead to more satisfying result.

The selected single tree volume curves are divided in two shapes. One follows a strong increase in the first 15 years and flattens down significantly after and the second follows a path with an exponential increase

of single tree volume. This shape could be explained through the clustering of the data and the flexibility of the applied functions. The clustering of observations at specific ages leads to a specific direction of the curve. The flexibility through the three coefficients allows the function to adopt many shapes without restriction as it is in the Bertalanffy function, through the power of three. Through this the two different curve shapes could be explained, but also further investigation is needed to verify the growth characteristics.
The 7 outliners which were not considered in the regression didn't had a big influence on the shape of the curves, nevertheless the excluding of them led to other results. Interesting would be to know if they were outliners because of a wrong age information or because they had an expectational growth.

The measured tree species grow in an agroforestry system and not in a natural forest or planation forest therefore the growth conditions were different against the trees for whom the growth equations were originally created. The growth of the conducted tree species is probably higher then under forest growth conditions. An increase or decrease of the growth for every tree species in forest stands can be predicted through the resistance against competition or if the tree is a light or shade arboreal.
The next fact which distort the growth characteristics are the different uses of the trees. Trees with the main purpose for shade, ornamental or backcloths will be preserved for a long time. In comparison trees which are used for poles or construction wood are often used in the age of 2 to 10 years which leads to a shortage of old grown trees. Which in conclusion creates a clustering of the data and reduces the prediction ability in higher or lower ages of certain tree species.

As last point the age determination through interviews shouldn't be forgotten. This way of age determination is easy, fast and convenient, but has still an unpredictable interference in itself through wrong testifies of the farmers. A more precise method would be through the analyzing of a drilling core of the wood. In a laboratory the drilling cores can be analyzed with the dendroecological method to determine the correct age (Rozendaal, 2011).

In the accomplished interviews the price for one timber from the same tree species wasn't connected to the dimensions of the sold timber. This result could be through the low number of interviews or different harvest and selling times. Even the prices from recent years vary greatly from farmer to farmer. The next reason could be the different qualities of the wood, which wasn't considered in this questionnaire.

The extra income of the trees can't be seen as an one-on-one extra income to the crops. Different trees have different effects on the crops and could therefore reduce or increase the yield of the crops. Moreover, the growing space of the crops is reduced because of the trees itself which leads to a reduced income.

6 Conclusion

The Petterson function is through the analysis of this thesis the recommended function to use in Stand-Height-Curves. *Markhamia lutea* achieves the highest Height-DBH relation and *Anitaris toxicaria* the second best.

The function of Richards is usable without restriction for the height, DBH and single tree volume curves. The DBH increment curve is led at an age of 75 by *Spathodea campanulata* with 199 cm, followed by *Ficus natalensis* with 143 cm. *Albizia coriaria* has the highest DBH at the age of 20 years with 63 cm.

The height curve is led by *Anitaris toxicaria* and *Markhamia Lutea* at the age of 20 years with 18 m and 17,7 m. The highest heights in the age of 75 years reaches decreasing in this order *Anitaris toxicaria* with 30,5 m, *Spathodea campanulata* with 24 m and Markhamia lutea with 21 m.

As a recommendation, for tree yield models in east African farm forestry systems, the function of Richards for the curves and Petterson for Stand-Height-Curves can be used in general. Considering that the verifying of the biological plausibility and a comparison with other new models is indispensable.

The farmers used their trees mainly for building material second for cooking and third for traditional uses. The highest harvesting monetary income achieves *Albizia coriaria* with 36,3 € for one tree, followed by *Ficus natalensis* with 13 €*, Anitaris toxicaria with 9,1 €* and *Markhamia Lutea* with still 8,8 € for one tree. The highest harvest volume after 20 years achieves *Albizia coriaria*, followed by *Ficus natalensis* and *Spathodea campanulata. Persea americana* has the lowest harvest volume at the age of 20 years with just 0,26 m^3 for a single tree.

The recommendation for investors is to intercrop *Albizia coriaria* at the moment and concerning the value of the wood only. Changing prices of the wood and different intercropped crops could lead to other recommended tree species.

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9 Appendix

9.1 Impressions from the farm site

Height measurement on a farm site; crops maize

View in a valley with swamps; crops: maize, tree: Persea americana

Diameter measurement at specific height on the farm of Sawagna; tree: Albizia grandibracteata

The farm site of Muwonge Kosma; crops: maize and beans, trees: Anitaris toxicaria

Path through a maize and bean field; trees: palms on the right, Ficus natalensis in the middle

On the farm of Muwonge Kosma; tree: Markhamia lutea in the middle right and palms, crops: beans

9.2 Interview

Interview

Date:

Farm:
Interviewee:

1) What is the purpose of this tree species:..?
   - ☐ fuelwood
   - ☐ charcoal
   - ☐ timber
   - ☐ roofing
   - ☐ poles
   - ☐ other
2) What was the amount of wood/product of trees of your last harvesting (tree size)?
3) Did you sell the product? If sold for how much, to whom and when?
4) Since when do you plant the tree species?
5) Are you satisfied with the growth of the planted tree species?
   - ☐ more than expected
   - ☐ as expected
   - ☐ less than expected
6) Where do you get your seeds/seedlings/plants from?
   - ☐ tree nursery
   - ☐ own
   - ☐ neighbor
   - ☐ government
   - ☐ organization
   - ☐ coppice
   - ☐ cuttings
   - ☐ seeds
   - ☐ stamps
7) Do you get any support/funding?
   a. If yes, from who? (name)
   b. What kind of support and how much?
      - ☐ Monetary
      - ☐ Goods/Tools
      - ☐ Teaching
      - ☐ other
8) Do you know other farmers who are growing this tree species to produce wood?
9) Do you plan to continue the tree growing?
   - ☐ Increase
   - ☐ same level
   - ☐ reduce
   - ☐ none

   why/explanation:

9.3 Field sheet

	Farm:						Date/ti me:						
	Area:						Soil description:						
Tree Nr.	Tree Species	Age in years	DBH in cm	Height in m	Lenght of commerc ial stem	Diameter at crown height	Diamet er at specifi	Occu rence	Silvicu ltural treatm	Silvicul tural score	sr in %	Proppse d cutting	Notes

9.4 Scientific and vernacular tree names

Vernacular name	Scientific name
Avocado	Persea americana
Gasiya/Akazia/Gasiva	Senna spectabilis
Girikiti	Erythriaa abyssinica
Jackfruit	Artocarpus heterophyllus
Kabalira	Ficus capensis
Kapulisasi	Cupressus lusitanica
Kasenene	Podocarpus latifolius
Kilowa	Jatropha curcas
Kirundu/Kilundu	Anitaris toxicaria
Kokowe	Ficus vallis-choudae
Luwawu	Ficus exasperata
Mango	Mangifera indica
Muboolo	Croton megalocarpus
Mugavu	Albizia coriaria
Mulinga	Moringa oleifera
Mululuza	Vernonia amygdalina
Munyaala	Spathodea campanulata
Musasa	Sapium ellipticum
Musizi	Maesopsis eminii
Musuga	Ehretia cymosa
Mutuba	Ficus natalensis
Muvule	Milicia excelsa (Chlorophora excelsa)
Muwawa	Acacia sieberiana
Mwambala butonya	Callistemon citrinus var. Splendens
Mwolola/Mwolora	Entada abyssinica
Ndagi	Combretum molle
Nongo	Albizia grandibacteria
Nsambya	Markhamia Lutea
Papaya	Carica papaya
Peera	Psidum guajava
Tuguneda/Tugunda/Matu	Vanquera apiculata
Kabweene	

9.5 Coefficients and statistical values of the analyzed functions

Diameter-Height-Development functions with their coefficients and statistical values

	Michailoff	Parable 2nd grade	Petterson
Markhamia l.	y=28,31239056*EXP(-15,74164077/D)+1,3	y=0,979123708+0,709927568*d+-0,004354665*d^2	y=1,3+(d/(2,453593043+0,306905352*d))^3
SSE	1068,390345	889,7421829	979,4734283
SEE	3,852110433	3,515327911	3,688332633
R^2	0,577	0,640	0,609
Ficus n.	y=24,06572676*EXP((-23,96182182/d)+1,3	y=5,891515581+0,149763065*d+0*d^2	y=1,3+(d/(3,543568622+0,33818848*d))^3
SSE	507,904	822,192	511,358
SEE	2,6559	3,379	2,664
R^2	0,767	0,621	0,764
Mangifera i.	y=17,30830949*EXP(-17,90490374/d)+1,3	y=1,213358033+0,383327996*d+-0,0025153*d^2	y=1,3+(d/(3,114817578+0,370795672*d))^3
SSE	82,43230169	69,95034101	75,59538938
SEE	1,657631862	1,526983312	1,587402379
R^2	0,813	0,838	0,826
Artocarpus h.	y=16,77539705*EXP(-13,92111805/d)+1,3	y=4,289874061+0,235692123*d+0,001175643*d^0	y=1,3+(d/(2,393865318+0,376904052*d))^3
SSE	195,5335263	191,3720747	131,4964546
SEE	2,79666606	2,76674592	2,293438071
R^2	0,429	0,440	0,439
Anitaris t.	y=32,3805463*EXP(-33,73258305/d)+1,3	y=6,207358102+0,167136854*d+0,000830047*d^2	y=1,3+(d/(4,76091362+0,298797202^d))^3
SSE	127,9188193	110,9797295	122,9548707
SEE	2,920260483	2,720045704	2,863038837
R^2	0,657	0,702	0,671
Persea a.	y=19,11866088*exp(-10,59935077/d)+1,3	y=5,867655629+0,296289234*d+0*d^2	y=1,3+(d/(1,59383974034005+0,367723579*d))^3
SSE	94,8335762	125,5701002	97,02371987
SEE	2,700905492	3,107931544	2,73191564
R^2	0,501	0,339	0,491
Albizia c.	y=21,29098367*EXP(-23,23486061/d)+1,3	y=2,521647638+0,163401574*d+2,04206E-05-05^2	y=1,3+(d/(3,694463,69446554554+0,380355007*d))^3
SSE	78,41533926	61,40398248	95,52302498
SEE	2,800273902	2,477982697	3,090679941
R^2	0,778	0,853	0,791
Spathodea c.	y=15,88016935*EXP(-10,89774934/D)+1,3	y=5,666854554+0,1901541*d+0,00038073*d^2	y=1,3+(d/(1,963740903+0,383760142*d))^3
SSE	48,18835483	39,86013183	45,99311722
SEE	2,313927753	2,104496029	2,26060752
R^2	0,522	0,602	0,545

Statistical values and coefficients for the height development functions

	Richards	Levakovich III	Gompertz	Bertalanffy
Markhamia l.	y=23,11789755*(1-EXP(-0,034729036*x))^0,462585755	y=23,02708913(x^2/(1311,064262+x^2))^0,213881444	y=20,80587307*EXP(-1,326669067*EXP(-0,100477071*x))	y=14,39448018*(1-EXP(-0,56756061*x))^3
SSE	1388,679686	1381,699989	1362,602438	1828,466949
SEE	4,391721515	4,380670911	4,350291238	5,039382332
R^2	0,430	0,433	0,441	0,276
Ficus n.	y=18,22805751*(1-EXP(-0,1249215*x))^0,849134732	y=18,74504239(x^2/(133,0538894+x^2))^0,370417354	y=17,83811551*EXP(-1,863886746*EXP(-0,201352027*x))	y=16,7782288*(1-EXP(-0,393842679*x))^3
SSE	809,9323897	802,3800588	790,3223945	912,2542293
SEE	3,353961981	3,338288107	3,31311031	3,559522107
R^2	0,627	0,631	0,636	0,603
Mangifera i.	y=112,006115*(1-EXP(-0,000396724*x))^0,483774021	y=54,71380127(x^2/(328104,0477+x^2))^0,242043695	y=21,44546292*EXP(-1,667656985*EXP(-0,242043695*x))	y=11,70118176*(1-EXP(-0,270676754*x))^3
SSE	101,37738	101,3479876	99,35965297	182,2743023
SEE	1,838272559	1,838006054	1,819886928	2,464915836
R^2	0,765	0,765	0,769	0,628
Artocarpus h.	y=103,5790387*(1-EXP(-0,000180257*x))^0,384461463	y=52,16066678(x^2/(869132,4367+x^2))^0,192181878	y=726,6826634*EXP(-4,724692576*EXP(-0,006117864*x))	y=12,49511032*(1-EXP(-0,34638422*x))^3
SSE	134,9884659	134,9700968	126,0039312	212,6972069
SEE	2,323690736	2,323532628	2,245029454	2,916828462
R^2	0,605	0,605	0,631	0,408
Anitaris t.	y=239,8392588*(1-EXP(-9,48632E-05*x))^0,416846224	y=96,59992797(x^2/(1416434,767+x^2))^0,208409839	y=71792,03516*EXP(-8,948241341*EXP(-0,003276703*x))	y=13,74125446*(1-EXP(-0,670798549*x))^3
SSE	123,4905004	123,4660881	83,57721157	285,5554266
SEE	2,869268204	2,868984584	2,360469043	4,36314433
R^2	0,671	0,671	0,776	0,243
Persea a.	y=13,98076229*(1-EXP(-0,297130878*x))^1,670945883	y=14,60740437(x^2/(24,72054178+x^2))^0,67678288	y=13,99986296*EXP(-2,346785062*EXP(-0,330035343*x))	y=13,70181312*(1-EXP(-0,421926148*x))^3
SSE	73,0464071	75,98036979	71,60211057	76,57577167
SEE	2,370433376	2,417569819	2,346881901	2,427023686
R^2	0,616	0,600	0,623	0,603
Albizia c.	y=18,05330558*(1-EXP(-0,077468441*x))^0,827723593	y=18,05330558*(1-EXP(-0,077468441*x))^0,827723593	y=17,92821087*EXP(-1,942187892*EXP(-0,133595658*x))	y=16,7753872*(1-EXP(-0,282667482*x))^3
SSE	81,50636844	81,65284782	77,81475555	124,2939851
SEE	2,854932021	2,857496244	2,78952963	3,525535209
R^2	0,761	0,760	0,772	0,690
Spathodea c.	y=29,82734441*(1-EXP(-0,012326023*x))^0,429006663	y=36,92620455(x^2/(25538,83045+x^2))^0,20524629	y=17,25274843*EXP(-1,222141227*EXP(-0,117335242*x))	y=12,30479305*(1-EXP(-0,589083017*x))^3
SSE	57,16722948	57,15271833	58,08789241	64,13691448
SEE	2,520300456	2,519980563	2,54051378	2,669517528
R^2	0,43	0,43	0,42	0,36

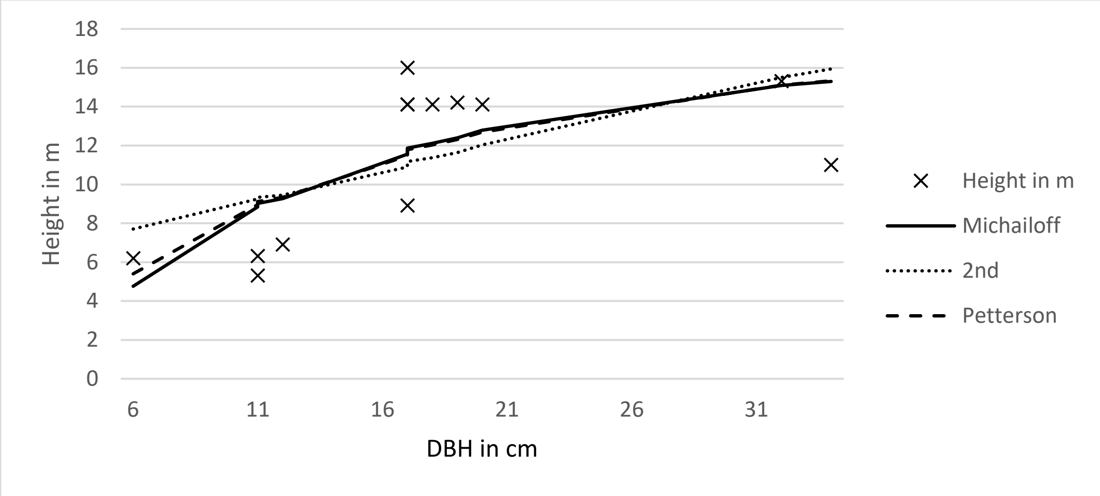
Statistical values and coefficients for the tree stem volume development functions

	Richards	Levakovich III	Hossfeld IV	Bertalanffy
Markhamia l.	y=1,163027635*(1-EXP(-0,134177202*x))^8,18178902	y=1,400404965*(x^2/(132,5991098+x^2))^2,79368069	y=x^1,132978578/(2,312237662+x^1,132978578/0,01832818	y=1,298375223*(1-EXP(-0,074208995*x))^
SSE	2,868727383	2,980600713	3,580238701	2,976861215
SEE	0,201008982	0,204890926	0,224557113	0,204762357
R^2	0,623	0,598	0,517	0,595
Ficus n.	y=15,71622732*(1-EXP(-0,146983415*x))^354,5577493	y=0,00048443*(x^2/(10644515,34+x^2))^1,270711824	y=x*2,54313078/(2075,739221+x^2,54313078/10107,32927)	y=437,2789577*(1-EXP(-0,00671956*x))^3
SSE	63,6	63,594	63,597	69,129
SEE	0,939	0,939	0,939	0,979
R^2	0,615	0,615	0,615	0,592
Mangifera i.	y=26655,78934*(1-EXP(-0,000100321*x))^1,79901466	y=38,27710856*(x^2/(65721,5952+x^2))^0,906379289	y=x^4,165620745/(5,802444088+x^4,165620745/6,5,29223E-07)	y=232,5592797*(1-EXP(-0,00546399*x))^3
SSE	0,695641776	0,69508008	1,281221408	0,857099707
SEE	0,154879461	0,15481692	0,210190505	0,171916149
R^2	0,763	0,763	0,646	0,732
Artocarpus h.	y=24,91866126*(1-EXP(-0,000789216*x))^1,00454777	y=24,28864479*(x^2/(1657790,74+x^2))^0,498281374	y=x^0,630098074/(116446,2752+x^0,630098074/7368,11365	y=0,670652515*(1-EXP(-0,096579104*x))^
SSE	0,907568506	0,907433897	0,994445329	0,971019352
SEE	0,19053278	0,19051865	0,199443759	0,197080628
R^2	0,534	0,534	0,533	0,506
Anitaris t.	y=1429,950912*(1-EXP(-1,6985E-05*x))^0,898368134	y=87,6988956*(x^2/(6963799,295+x^2))^0,448989633	y=x*0,898298669/((13,48195181+x^0,898298669)/13656,95282)	y=1,458293345*(1-EXP(-0,130960143*x))^3
SSE	1,339482238	1,339494022	1,339498827	1,234002221
SEE	0,298829075	0,298830389	0,298830925	0,286821922
R^2	0,604	0,604	0,604	0,640
Persea a.	y=0,254627488*(1-EXP(-1,632060926*x))^224014,699	y=0,2922838*(x^2/(0,066528216+x^2))^697,976221	y=x*1,082168155/(70,28975575+x^1,082168155/1,070660702	y=0,274345549*(1-EXP(-0,199315591*x))^
SSE	0,136565063	0,145617539	0,149381985	0,148111224
SEE	0,102493926	0,105836426	0,107195718	0,106738798
R^2	0,497	0,446	0,431	0,435
Albizia c.	y=2,408344717*(1-EXP(-1,132768081*x))^24133,66903	y=2,532808073*(x^2/(1,012290561+x^2))^129,6857804	y=x*1,238975387/(54,94720163+x^1,238975387/124,8043516)	y=2,484347009*(1-EXP(-0,087543112*x))^3
SSE	6,585237654	6,91470749	42,47531596	34,17363579
SEE	0,811494772	0,831547202	2,06095405	1,848611257
R^2	1,000	0,996	0,984	0,991
Spathodea c.	y=26,11131967*(1-EXP(-0,00636381*x))^1,645847603	y=297,0038155*(x^2/(670571,1208+x^2))^0,796610541	y=x*1,596851638/(148,7063508+x^1,596851638/381,8807841)	y=1,115363517*(1-EXP(-0,097395203*x))^3
SSE	9,131	46,207	0,02371868	0,724338144
SEE	1,007	2,265	0,051336234	0,2836
R^2	0,856	0,856	0,856	0,845

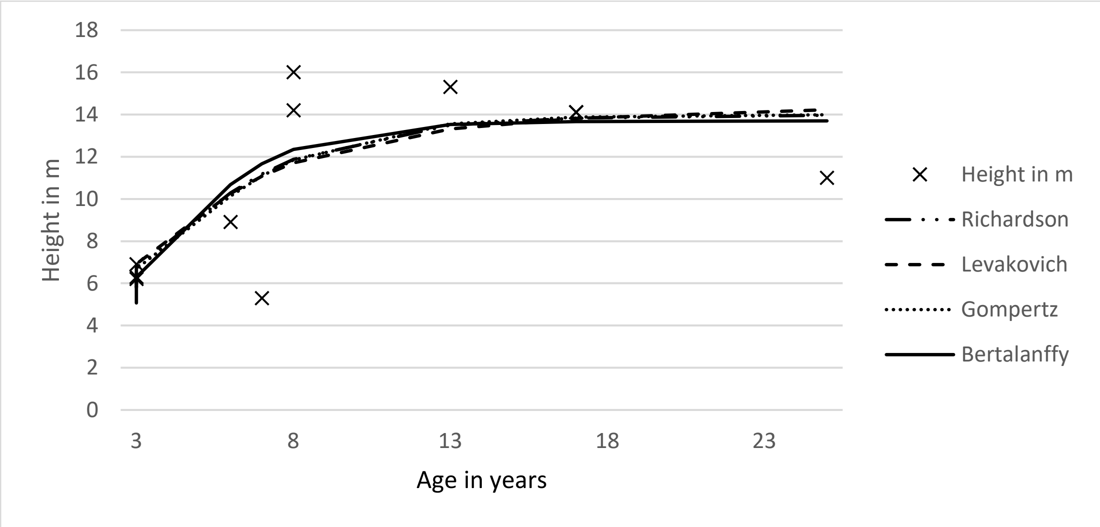
9.6 Tree growth diagrams

Persea Americana

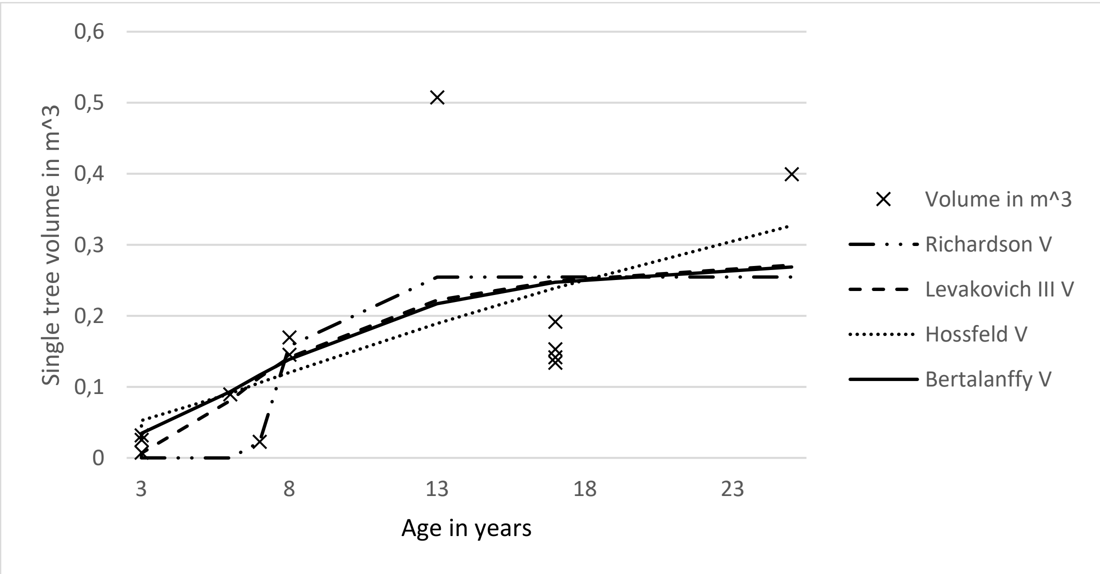
Diameter-Height-Development of Persea americana



Height development of Persea americana

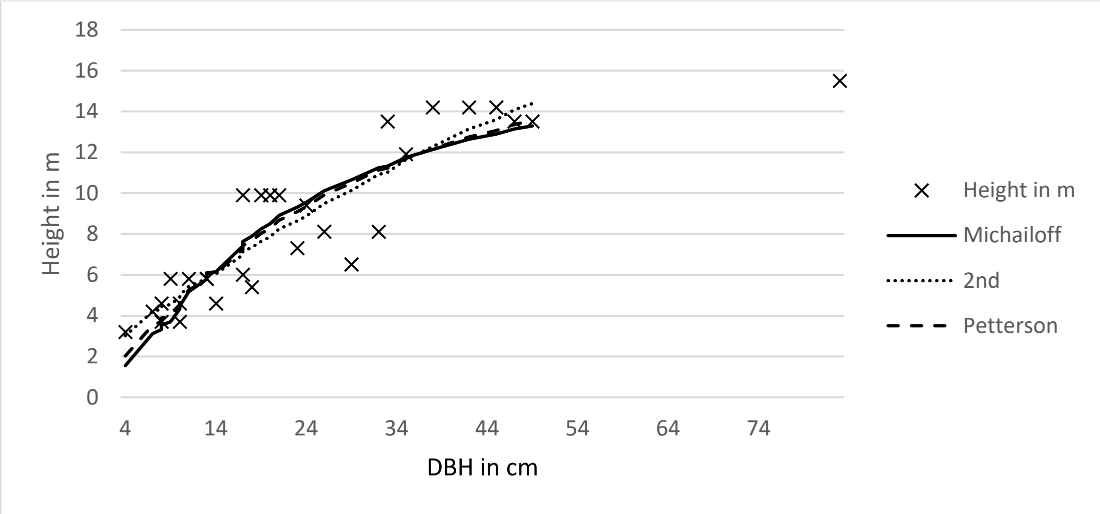


Tree stem volume development of Persea americana

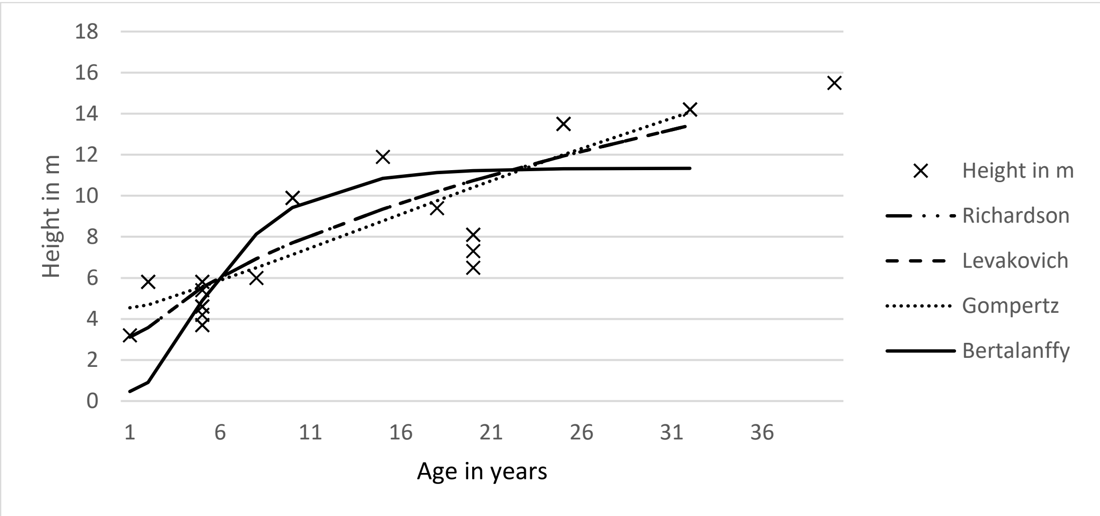


Mangifera indica

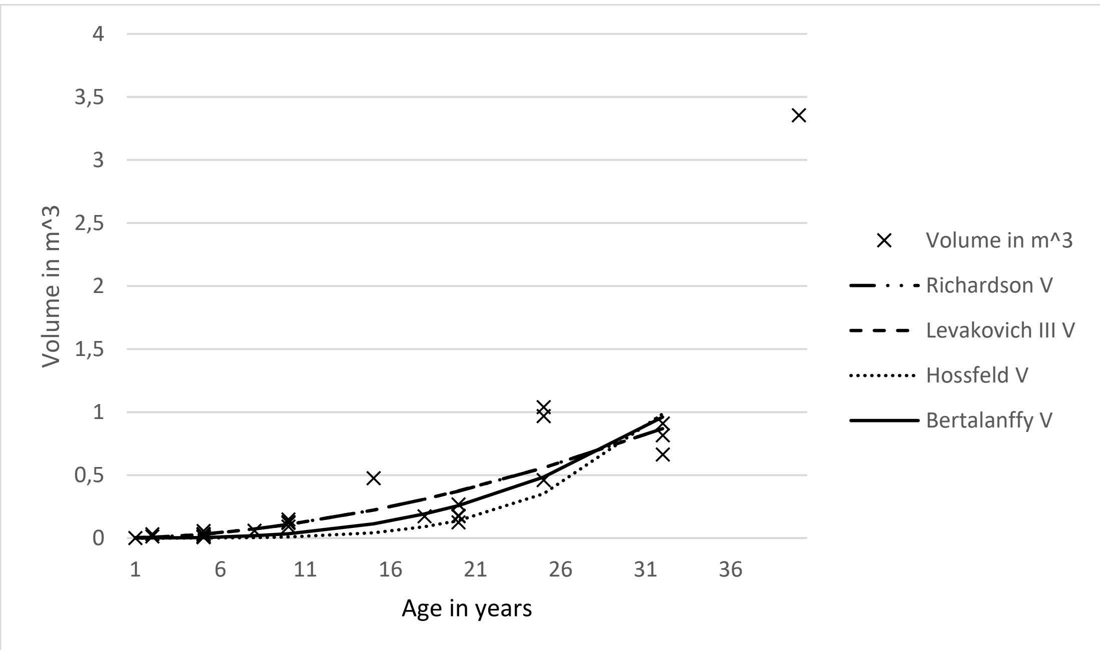
Diameter-Height-Development of Mangifera indica



Height development of Mangifera indica

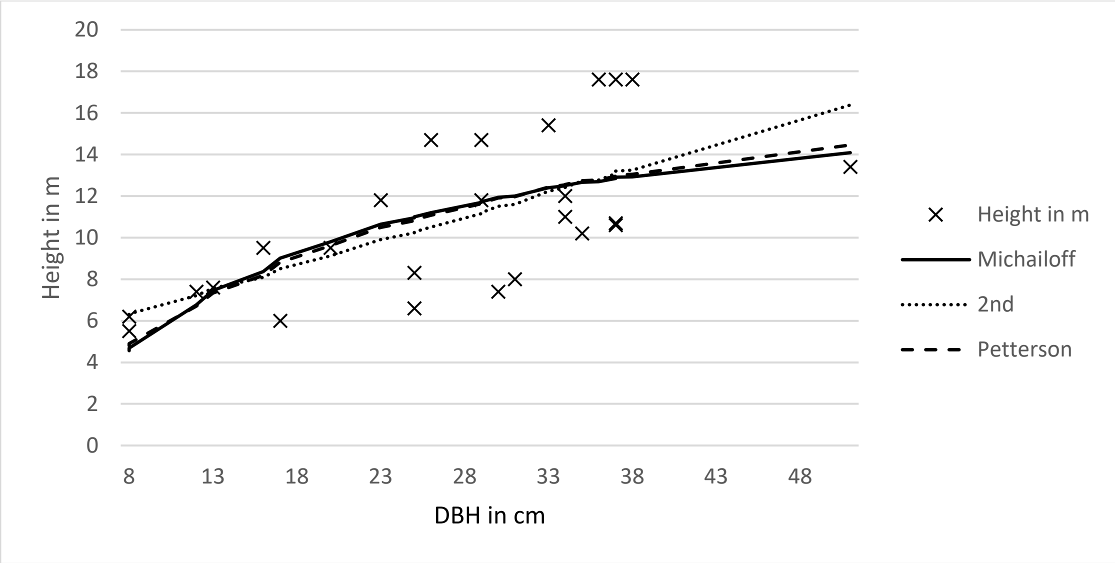


Tree stem volume development of Mangifera indica

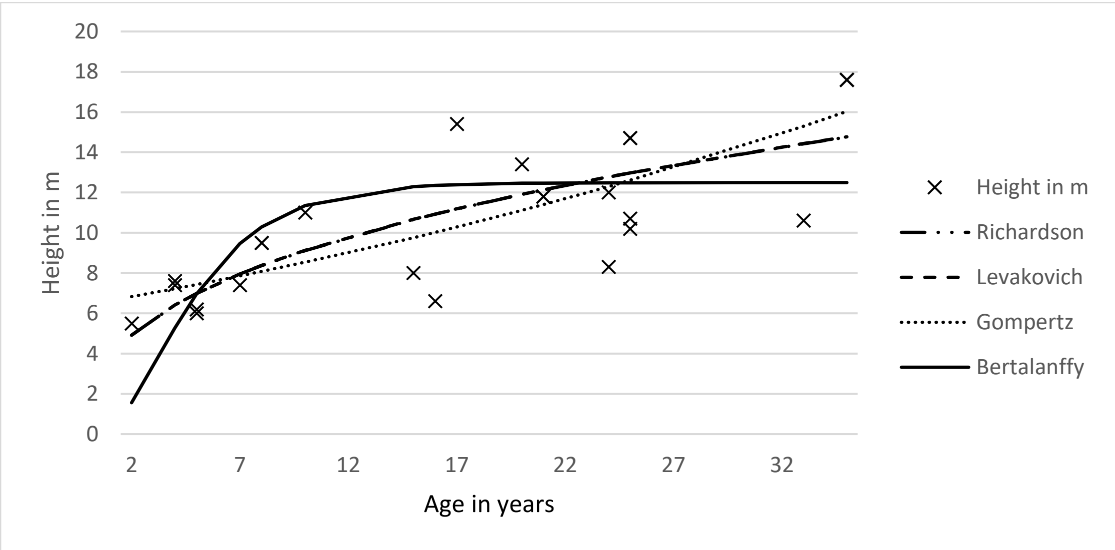


Artocarpus heterophyllus

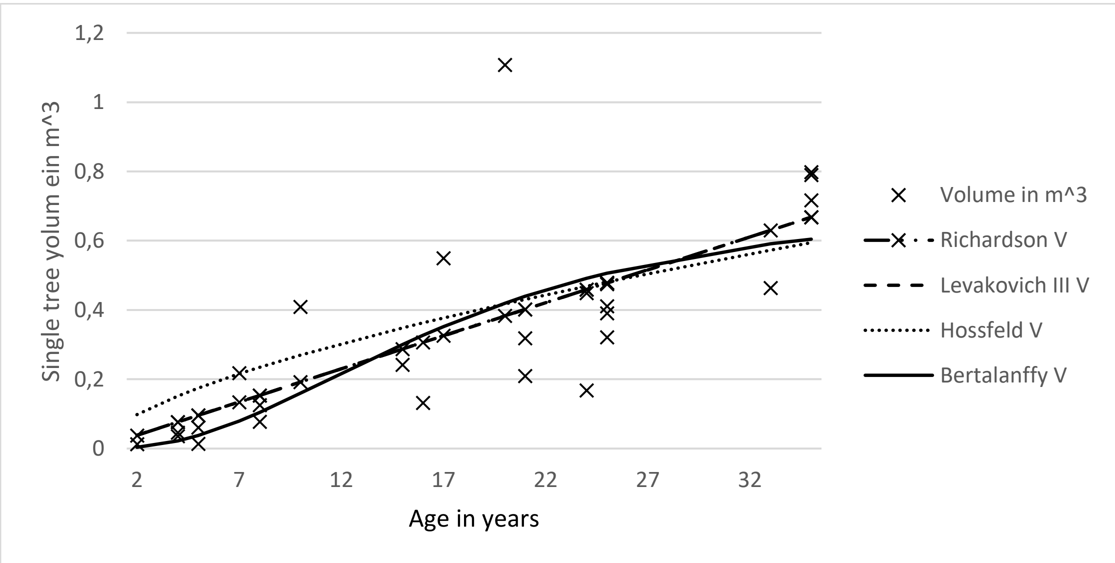
Diameter-Height-Development of Artocarpus heterophyllus



Height development of Artocarpus heterophyllus

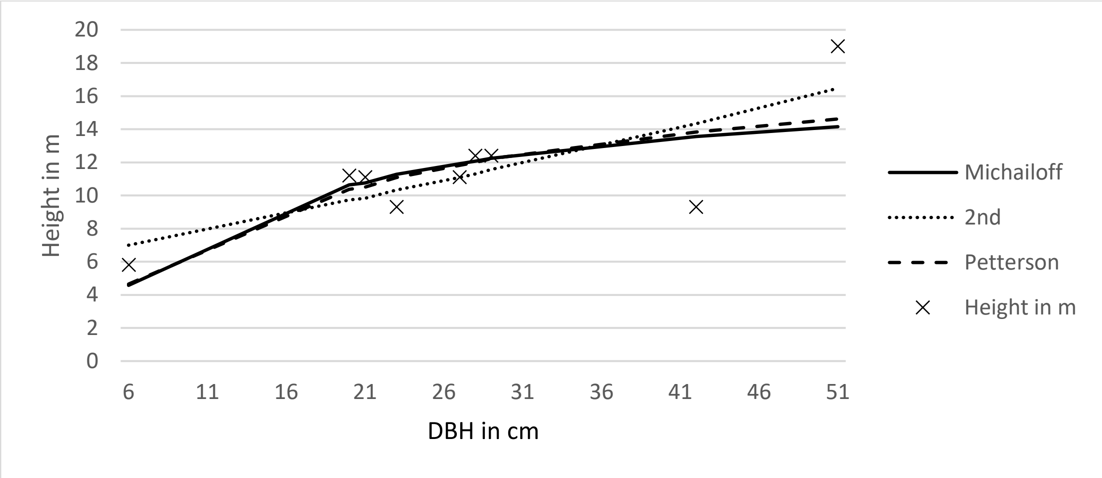


Tree stem volume development of Artocarpus heterophyllus

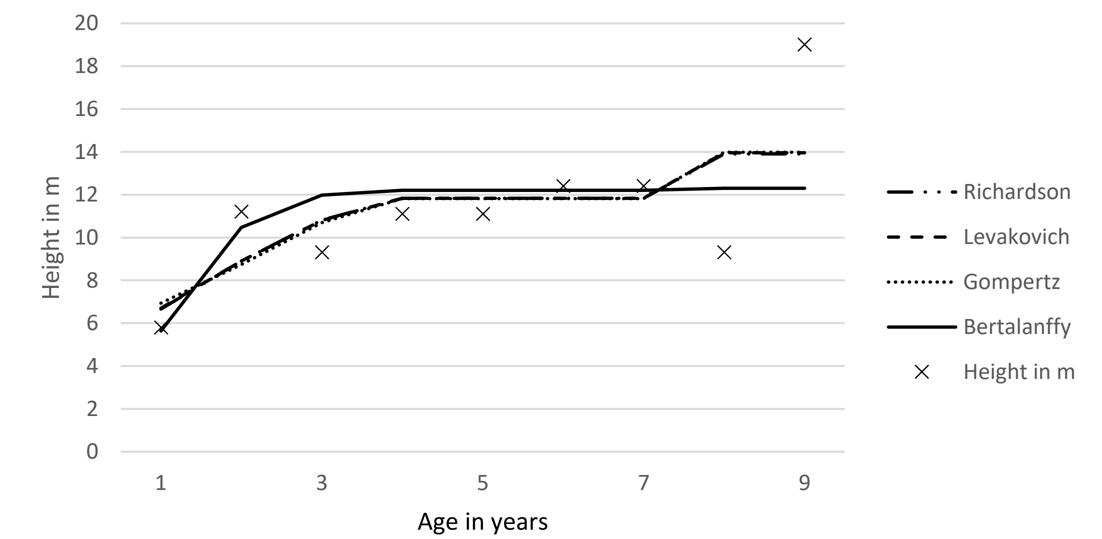


Spathodea camapnulata

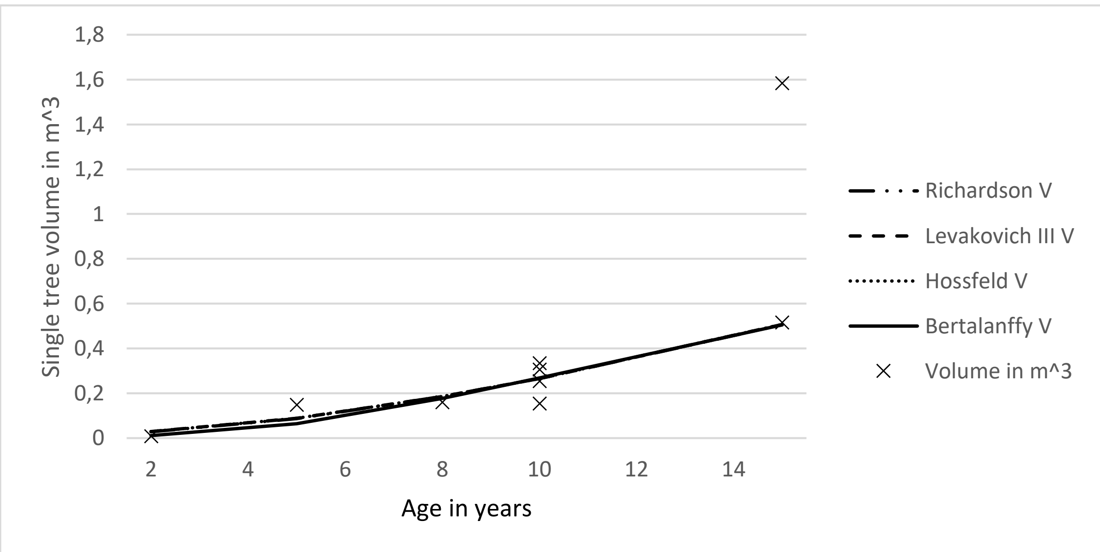
Diameter-Height-Development of Spatodea campanulata



Height development of Spatodea campanulata

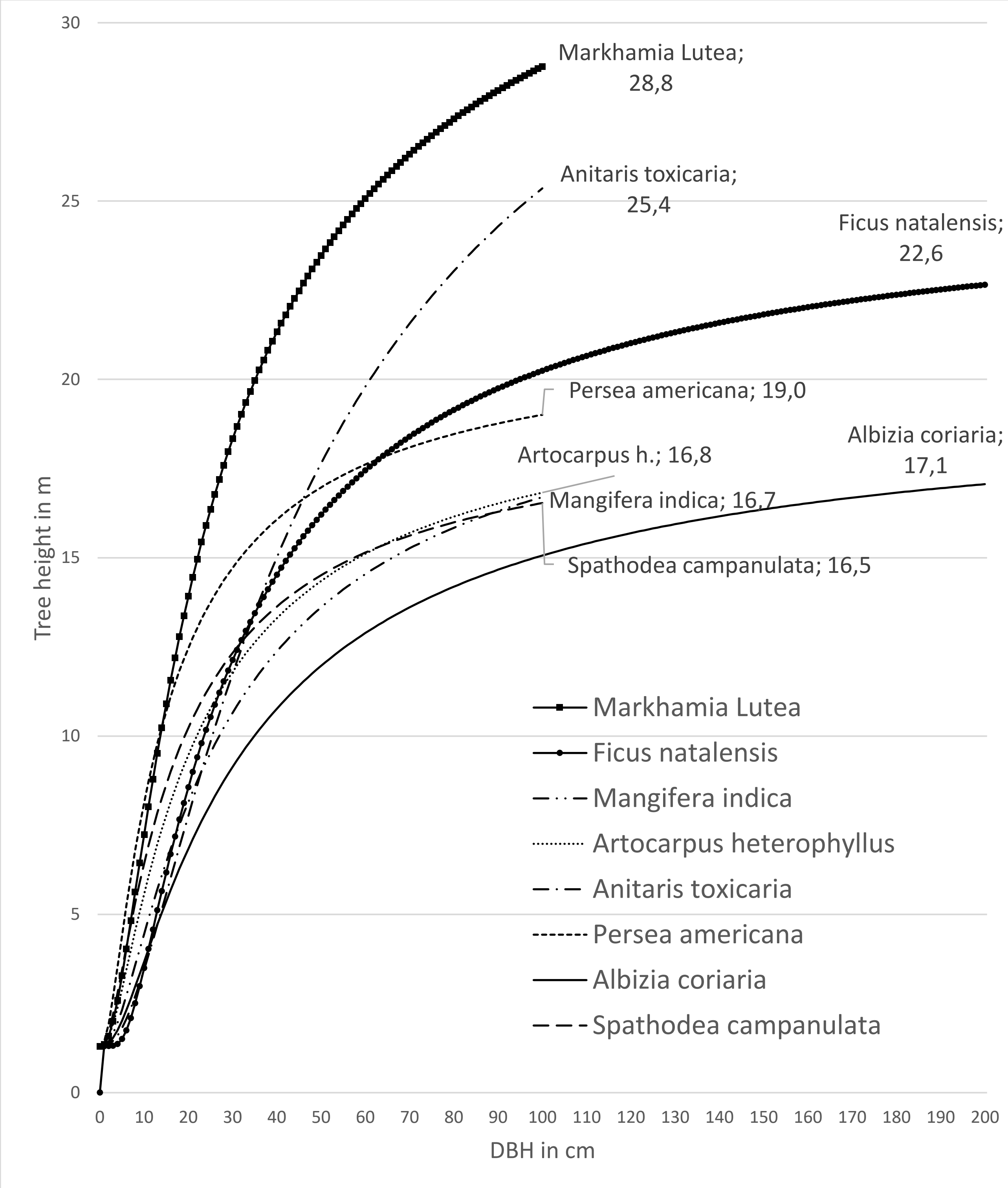


Tree stem volume development of Spatodea campanulata

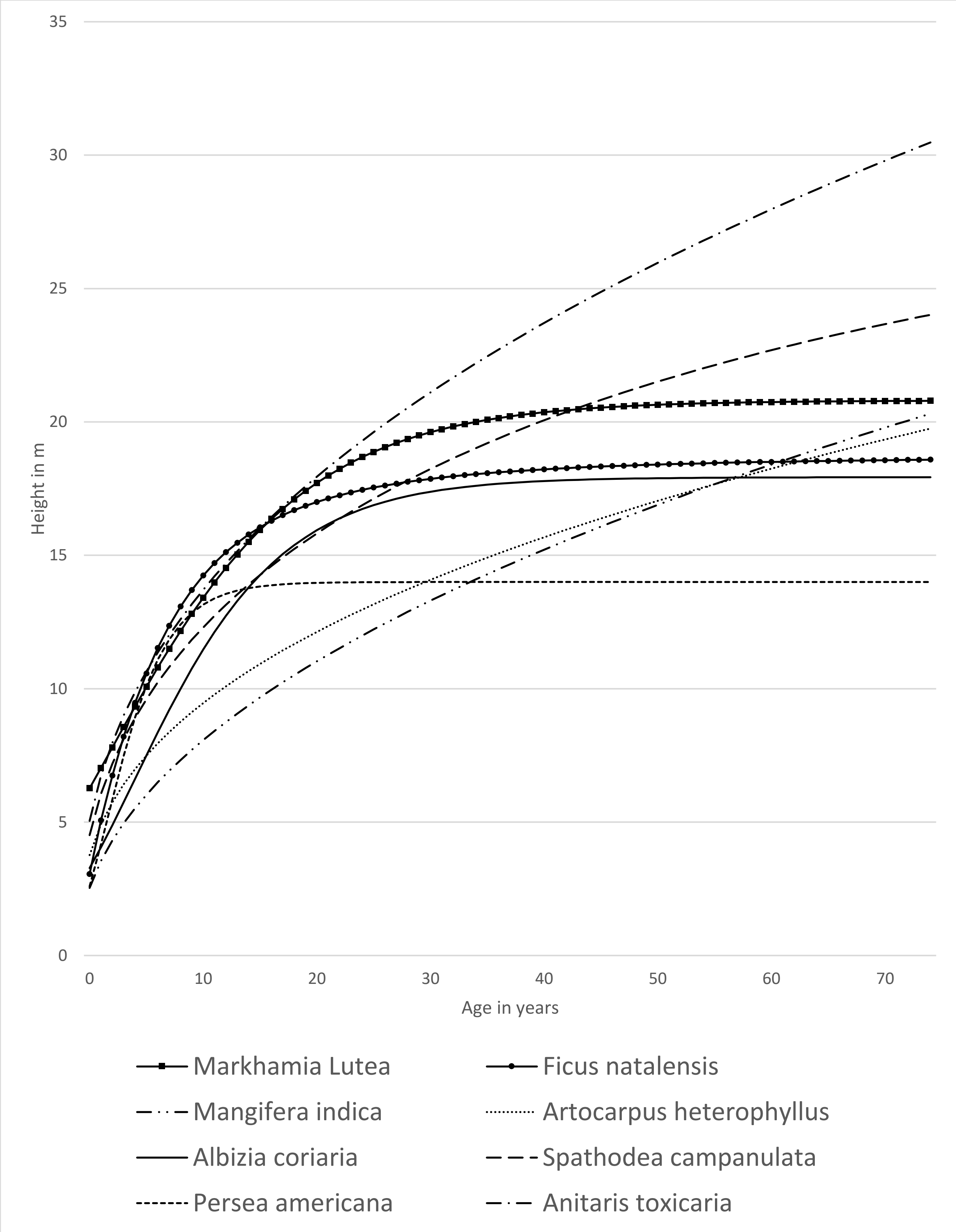


9.7 Extrapolated tree growth diagrams

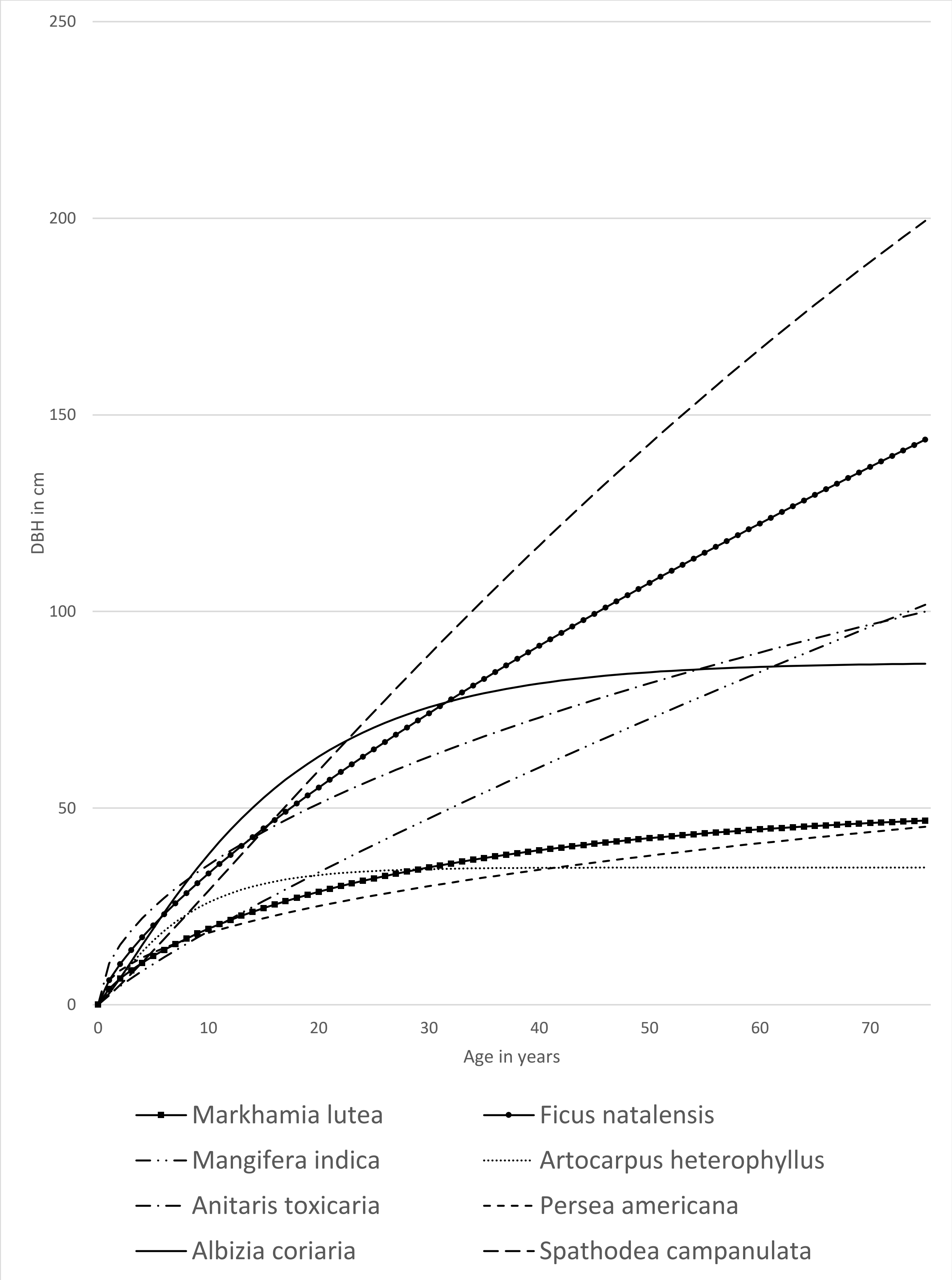
Extrapolated Diameter-Height-Development to a DBH of 200cm for all tree species



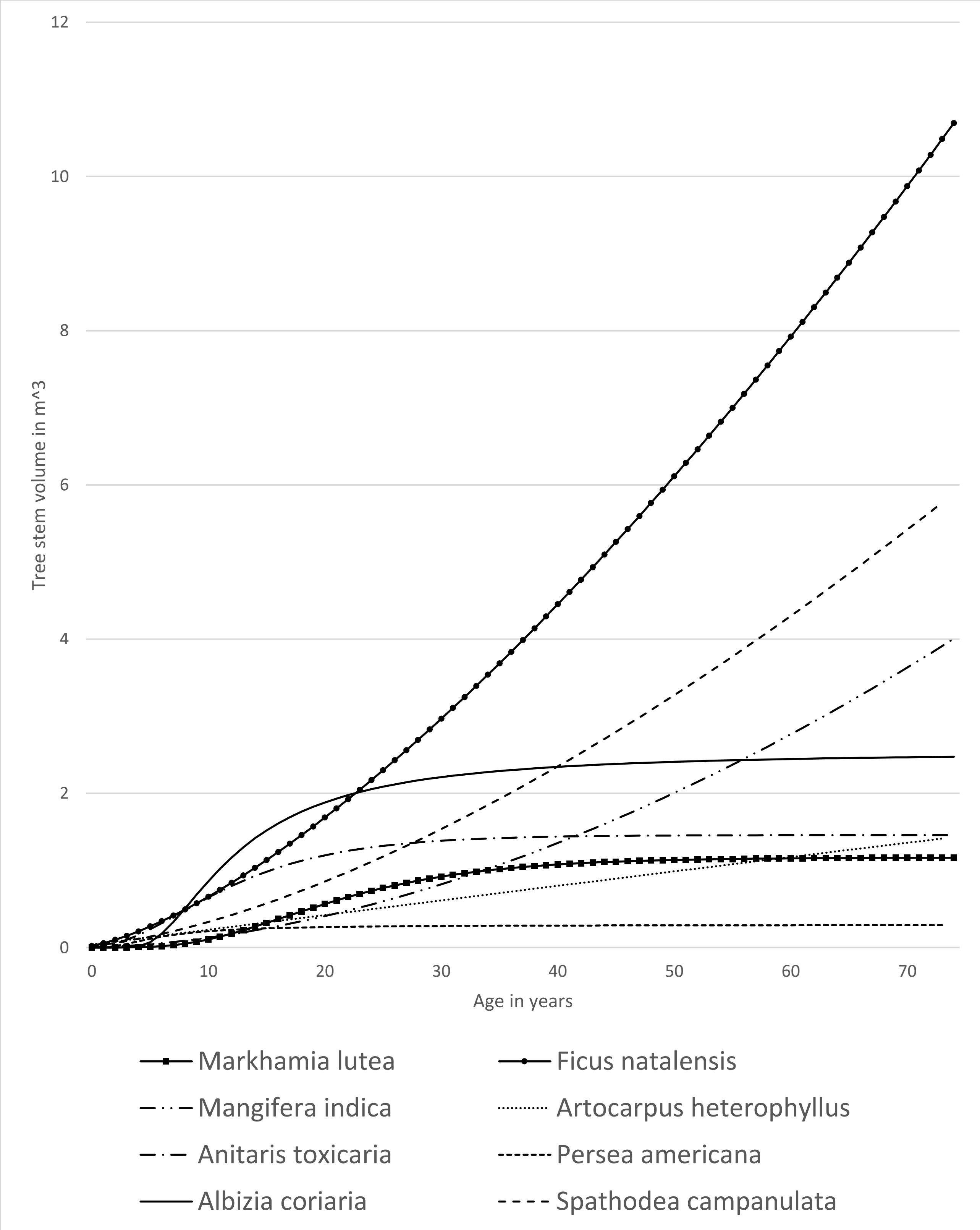
Extrapolated height development over age for the tree species



Extrapolated DBH development till the age of 75 years



Extrapolated tree stem volume till the age of 75 years



9.8 Filled-out field sheet

Farm: Nseveco

Area: Nakasozi

Coordinates:

Size of farm:

Date/time: 29.3.18

Soil description: CL 7.5YR 3/2

pH: 5 at Lukoya Moses

Tree Nr.	Tree Species	Age in years	DBH in cm	Height in m	Lenght of commercial stem	Diameter at crown height	Diameter at specific	Occurence	Silvicultural treatm	Silvicultural score	sr in %	Proppsed cutting	Notes
	Jackfruit	16	25,2	6,6	2,4		23,8	0	P	2			
	Mutuba	13	12	6,8	1,8			0	P	2			Terminal Knospe [illegible]
	Mahogany	8	15,6	8,9	2,2	14,9		0	P	2	100	8	
	-"-	8	16	9,8	3,1		14,8	0	P	1	100	8	14,8 at 2,3
	Mugavu	7	19	5,6	2,7	14		0	P	2			Setzling
	Lukoya Moses												
	Mutuba	2	5	4	3	4,5		0	/	1			for shade / [illegible]
	Kilundu	8	35,8	11,9	5,8		29,6	1		1			at 3,8
	-"-	5	25,5	11,2	4,8		22,6	1		1			-"-
	-"-	5	27	11,6	5,2		23,1	1		1			-"-
	-"-	5	28,3	13,2	6,3		25,3	1		1			-"-
	-"-	3	22,3	7,6	5,2		19,1	1		1			-"-
	Nongo	8	33	14	5,2		29,7	0		1			
	Mugavu	8½	~~37~~	11,4	4,4	25,7		1		1			
	Musugaga	34½	45	12	6			1		1			
	Mutuba	9	53,9	22	5,6		27/44,1	1		2	100		3,8
	Mutuba	9	33	13,7	3,8		24/30,5	2		2			-"-
	Mugavu	3	13,2	3,5	13,2	13		2		3			
	Nongo	8	30	13	3,2	30,2	23,4/28	1					at 3,8
	Munyaala	10	28/29,3	12,4	5,6		24,8/25,4	1		2			3,8
	Mutuba	9	33	16	3,2		27/30	1		2			-"-
	Munyaala	15	51,5	19	6,2		42	1		2			-"-

Nongo = Albizia - grandibracteata

Musugu = Ehretia cymosa

Olea capensis welwitschii

9.9 Completed interview form

Interview

Farm: Sempewo Mark

Interviewee:

Date: 3.4.18

1) What is the purpose of this tree species: Mutuba?
   - [x] fuelwood
   - [ ] charcoal
   - [x] timber
   - [ ] roofing
   - [ ] poles
   - [ ] other
   - [x] Barkcloths
2) What was the amount of wood/product of trees of your last harvesting (tree size)?
   50 timber. each at 5000 UGX ; 25 years old ; cut this year
   7 feet x 7 feet x 2 inch
3) Did you sell the product? If sold for how much, to whom and when?
4) Since when do you plant the tree species?
   1993
5) Are you satisfied with the growth of the planted tree species?
   - [ ] more than expected
   - [x] as expected
   - [ ] less than expected
6) Where do you get your seeds/seedlings/plants frpm?
   - [ ] tree nursery
   - [ ] own
   - [x] neighbor
   - [ ] government
   - [ ] organization
   - [ ] coppice
   - [x] cuttings
   - [ ] seeds
   - [ ] stamps

   10 feet high and 4 inch in Ø
7) Do you get any support/funding?
   a. If yes, from who? (name)
   b. What kind of support and how much?
   - [ ] Monetary
   - [ ] Goods/Tools
   - [ ] Teaching
   - [ ] other
8) Do you know other farmers who are growing this tree species to produce wood?
   Many
9) Do you plan to continue the tree growing?
   - [x] Increase
   - [ ] same level
   - [ ] reduce
   - [ ] none

   why/explanation: to get money, shade and bark clothes

9.10 Utilizations and values of different tree species

Interview nr.	Farmcode	Tree species	What is the purpose of this tree species?	What was the amount of wood/product of trees od your last harvesting?	Since when do you plant	Are you satisfioed with the	From where do you get	In which form do you get	Do you get	Do you plan to continue	Reason
1	KSH	Albizia coriaria	fuelwood, charcol, timer	15000UGX for one timber	1998	as expected	neighbor	seeds	No	same level	to old to take care
27	KyMA	Albizia coriaria	charcoal,timber	8000UGX for one timber in 2014, 20 timber		less than expected	tree nursery	seeds	No	increase	plting for sons and grandsons
2	NN	Albizia coriaria	fuelwood, charcol, timber	12000UGX for one timber (40timbers) + 7000UGX for one blit (20blits) in 2014, big tree; 21 timbers and charcoal out of branches, small tree	2000	as expected	own	seeds	No	none	high competition, afect on the growth of maize
3	NN	Albizia coriaria	poles								
4	Sawmill	Albizia coriaria	timber	buys at 8000UGX sells at 10000UGX							
5	KSM	Anitaris toxicaria	fuelwood, shade, timber	4000UGX for one timber at 30y. In 2008, 75 timber	1992	as expected	own	seeds	No	increase	provide money if sold, remaining branches for fuelwood
6	KyK	Anitaris toxicaria	fuelwood, charcoal, timber	3500UGX for one timber at 31y. In 1980	1951	as expected	neighbor	by birds	No	none	Eucalyptus got a better value and grows faster, Mutuba for shade and leaves contribute to the soil fertility
7	NI	Anitaris toxicaria	timber, shade	500UGX for one timber at 22y. In 2014, 42 timber; 500UGX for one timber in 2017, 100 timber	1991	as expected	own	seeds	No	increase	no effect to othe rcrops, grows fast and to preserve th eenvironment
8	NLM	Anitaris toxicaria	fuelwood, bark clothes, timber	3000UGX for one timber (nowadays 13000UGX) at 30-35y. In 1994, 100 timber	2010, grandfath er since	as expected	own	seedlings	Yes, NGO Aliance	increase	grow fast and source of income
4	Sawmill	Anitaris toxicaria		buys at 5000UGX sells at 6000UGX							
10	NNP	Artocarpus heterophyllus	fuelwood, charcoal, fruits	one Jackfruit 3000-4000UGX	2000	as expected	neighbor	seeds	No	same level	for home consumption
18	KML	Cupressus lusitanica	fuelwood, charcoal, fencing, ornamental		1988	as expected	tree nursery	seedlings	No	same level	takes long to mature and has no market
19	KKM	Ficus natalensis	timber, shade, bark clothes		1959	more than expected	own	seeds	No	increase	for shade and timber afterwrds
21	KMJ	Ficus natalensis	shade, bark clothes		1975	as expected	neighbor	cuttings	No	same level	to old to take care
22	KSH	Ficus natalensis		5000UGX for one timber at 56y.							
24	KSM	Ficus natalensis	fuelwood, bark clothes, timber	5000UGX for one timber at 25y. In 2018, 50 timbers	1993	as expected	neighbor	cuttings	No	increase	bark clothes, shade, money
9	KyKI	Ficus natalensis		5000UGX for one timber at 70y. In 2017, 60 timber							
11	NNP	Ficus natalensis	timber, shade	1500UGX for one timber at 20y. in 2010	2009	as expected	own	cuttings	No	increase	shade for coffee
4	Sawmill	Ficus natalensis		buys at 6000UGX sells at 8000UGX							
12	KKI	Markhamia Lutea	timber, fueklwood, poles, roofing	10000UGX for one timber at 20y., 7 timber; 7000UGX for one blit; 10000UGX for one timber at 32y., 20 timber	1976	as expected	own	seedlings	No	same level	got already enough, will just look after the coppices
13	KKV	Markhamia Lutea	fuelwood, poles, roofing, timber	2000-3000UGX for each pole at 1y., 25 poles; 5000UGX for one timber at 20y. 20 timber	1988	as expected	own	coppice, seeds	No	same level	want to grow eucalyptus for poles and timber, one electrical pole 150000UGX
14	KSH	Markhamia	roofing, poles	3000UGX for one pole at 3y.	1973	as expected	neighbor	coppice,	No	same level	to old to look after them
15	NG	Markhamia Lutea	timber, roofing	1500UGX for one pole at 6y. In 2013,	1995	as expected	own	seeds	No	same level	regenerate by it's own, noo investment
4	Sawmill	Markhamia Lutea		buys at 8000UGX sells at 10000UGX							
16	KyMC	Moringa oleifera	medicine, shade, preserve environmnet	200000UGX for one tree at 10y.	2008	as expected	neighbor	seeds	No	increase	for medicine to sell it to doctors
17	KyKI	Muboga		5000UGX for one timber at 70y. In 2008, 57 timber							
20	NLM	Mubooloo	fuelwood, charcoal, timber	7000UGX for one blit at 10y. In 2013, 30 blits	2002	more than expected	neighbor	seeds	No	increase	shade für coffee and blits for construction
25	KM	Sapium ellipticum		600UGX for one timber at 26y. In 2018, 20 timber							
26	KSM	Senna spectabilis	timber, roofing, poles, shade	10 poles at 3y. And 20 blits in 2017	1998	as expected	neighbor	s	No	increase	as boundary to provide more firewwood and poles

STATUTORY DECLARATION

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Dresden, ...01.08.2018............................ Krombholz
....

signature